

*The
Great World
Encyclopedia of
Science*



Science*

letters

To Lex,

Wishing you a very happy
birthday and many hours of
enjoyable reading

with love from

Mummy and Daddy.

26th June 1977

9th
birthday.

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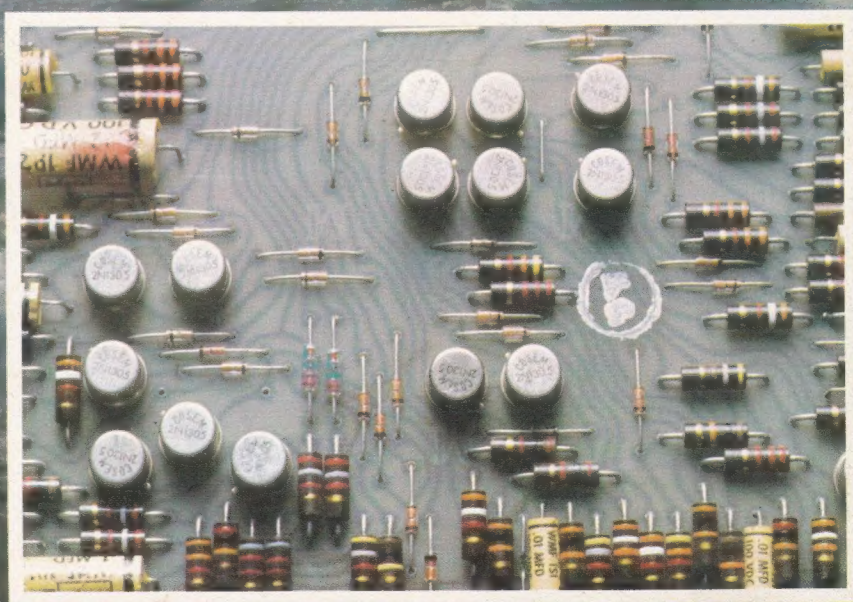
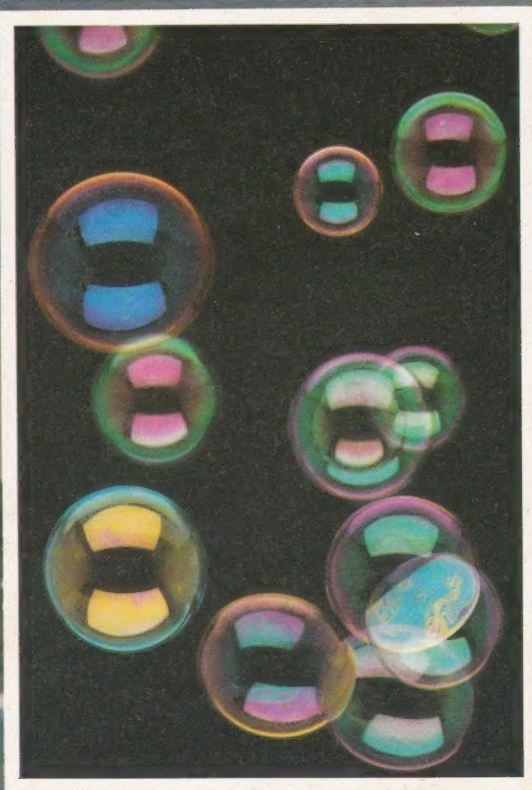
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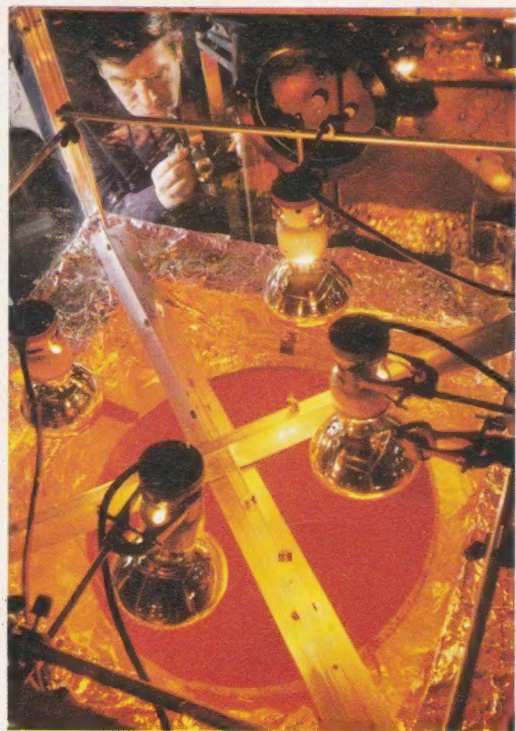
Science

Great World Encyclopedia of
Science

Alexis.



Great World Encyclopedia of
Science



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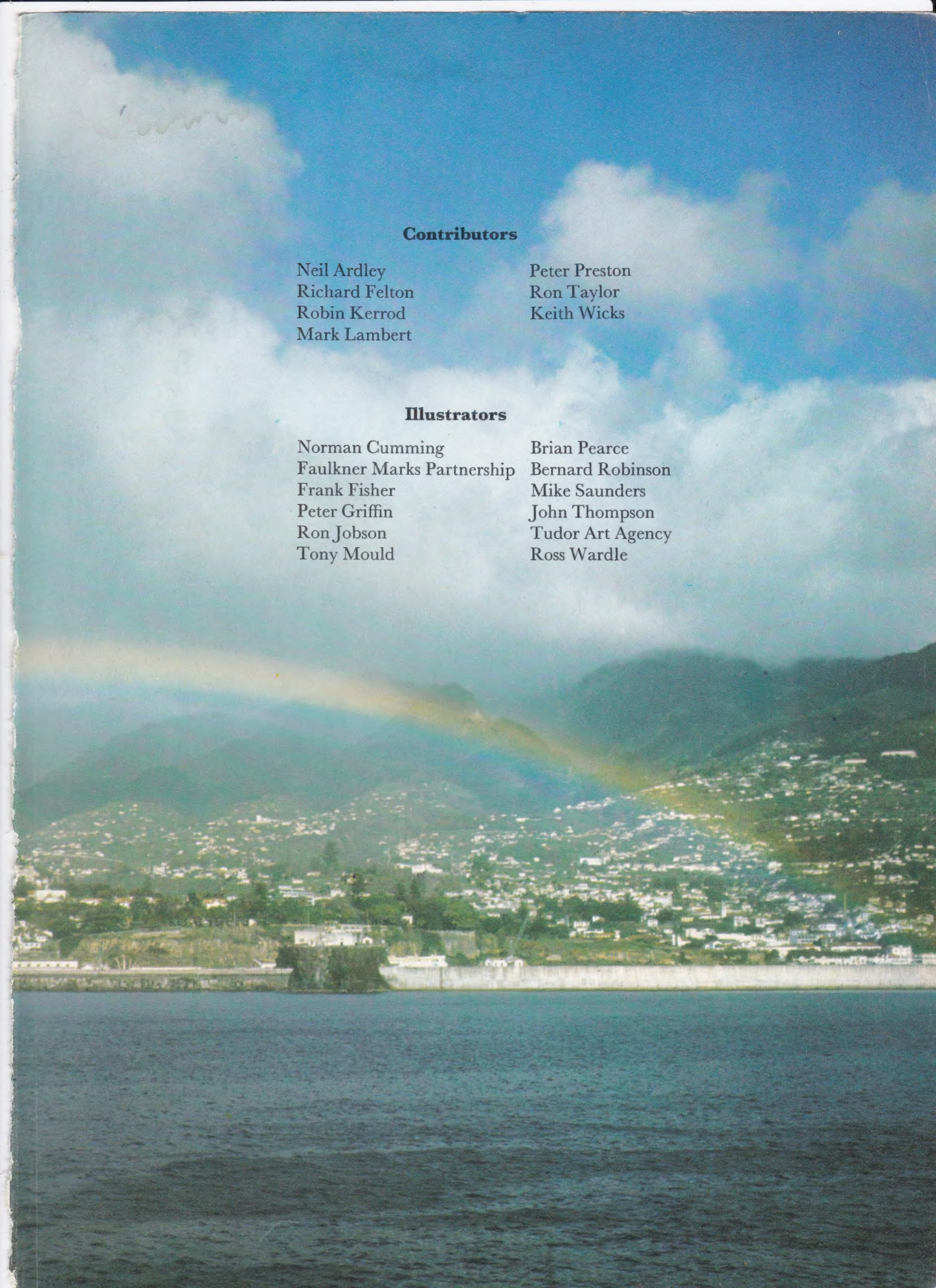
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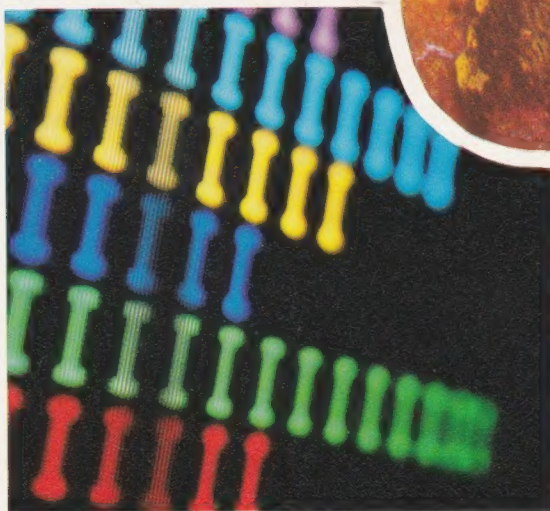
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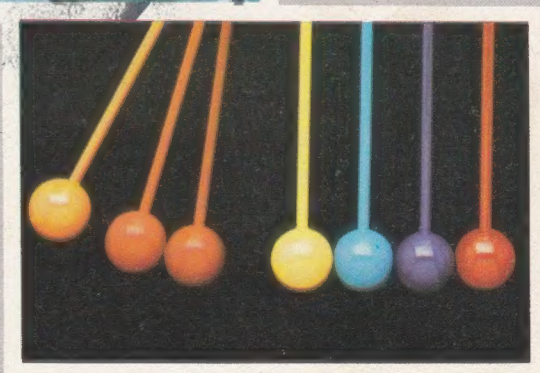
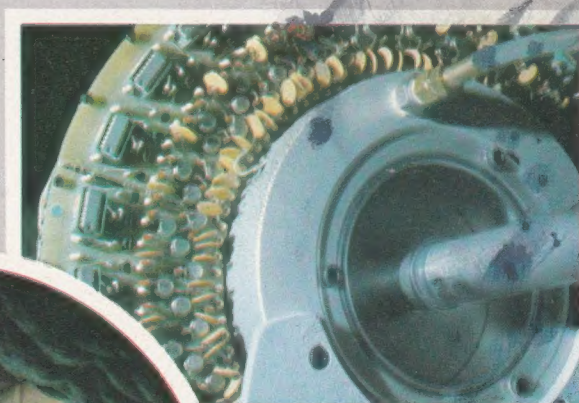
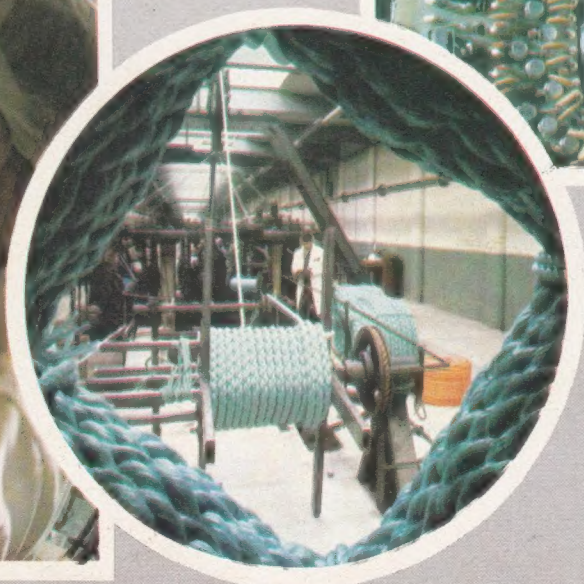
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Science through the Ages

Below: Stonehenge was constructed about 1500 B.C.



From the Beginning

Early man had no time to stop and wonder. His wandering way of life was a struggle for existence that depended upon performing extremely practical tasks. In order to make this struggle easier he fashioned tools and weapons from bones and stone. At the same time he learnt to use fire to cook his food and to keep away fierce animals.

In the course of time, man began to settle down. He gradually changed his way of life from hunting to farming. When this happened, he was able to begin to develop a technology. He constructed tools from iron and bronze and built more permanent places to live in. Some elaborate structures, such as Stonehenge (c. 1500 B.C.) date from this time.

One of the earliest sciences to be developed was geometry; it helped in the construction of buildings and the marking out of land for farming. But perhaps the most important advance during these early years was the discovery of the wheel. This simple addition to man's knowledge revolutionized his way of life.

The Greek Thinkers

With the rise of great cities and empires some men were able to take time to think about matters which were not directly concerned with the everyday practicalities of life. This was particularly true in early Greek society. Aristotle (c. 400 B.C.) made one of the greatest contributions to science by recognizing the importance of observation and the classification of knowledge. Geometry, which had been developed thousands of years earlier, was perfected by the Greeks Thales, Pythagoras and Euclid in about 200 B.C. More practical studies were carried out by men such as Archimedes.

As well as studying things that were immediately to hand, the Greeks also developed ideas about the world and the universe. The stars were mapped, and the size of the Earth was measured with surprising accuracy. Ptolemy (A.D. 100s), in a series of books called the *Almagest*, presented an idea of the universe in which all objects in the sky revolved round the Earth.

Through the Dark Ages to the Renaissance

The Romans did little to develop scientific thought. They were mainly interested in applied science, such as engineering. With the fall of the Roman Empire, progress in science ceased almost completely. Only in the East did true scientific ideas survive. The Arabs learned the decimal system of numbers from the Indians, and they developed

Above: An illustration of Ptolemy's Earth-centred universe, from *Harmonica Macrocosmica* by Cellarius.

Right: Arab astronomers at work in the Istanbul Laboratory.



algebra. The Chinese were the greatest of the ancient technologists. They invented silk and paper, the crossbow, the wheel barrow, the ship's rudder, gunpowder, and many astronomical instruments. The Chinese also had a remarkable knowledge of chemicals and medicines. But none of these discoveries reached Europe at the time. Many of them, in fact, had to be rediscovered in later years. In Europe, during the Middle Ages, theology was considered more important than science. People were discouraged from having new ideas, and had to accept those of Aristotle and Ptolemy — with all their inaccuracies. Those who disagreed were considered heretics and put to death.

The Renaissance, or 'rebirth', began first with art and literature, but gradually new scientific ideas began to emerge. Leonardo da Vinci studied anatomy, but his drawings and ideas were not published until much later. Copernicus reversed Ptolemy's idea of the universe, suggesting that the Earth revolved around the Sun. In the late 1500s and early 1600s Tycho Brahe and Johannes Kepler developed this idea, and Kepler showed that all the known observations could be accounted for if the planets had elliptical paths around the Sun.

The science of chemistry had, until this time, consisted of ideas confused with magic. The alchemists of the Middle Ages had taken the ideas of Aristotle and the technology of the Arabs and mixed them up with religion and astrology. In the 1660s Robert Boyle first introduced the scientific method into chemistry. He defined a chemical element and put forward theories of the nature of matter.

The Start of Modern Science

It is difficult to say when modern science actually began. Some scientific principles in use today were discovered by the Greeks. But in the early 1600s there lived two men whose ideas have had a lasting effect. They were Galileo and Sir Isaac Newton. Galileo's greatest contribution was to recognize the importance of observation, careful measurement, and planned experiments. He investigated many areas of physics, including the study of falling bodies. He developed a telescope that enabled him to make several astronomical discoveries that lent support to Copernicus' theory of the universe. Newton developed the modern theory of gravitation. This was the first time that anyone had devised a theory that made all the previous observations of other scientists fit together. Newton's great contributions to the progress of science, therefore, was to organise ideas to explain events. It is in just this way that all modern science advances.

The Scientific Revolution

From the 1700s onwards science began to progress more rapidly. At this time scientists were mostly amateurs, and, as so little was



Above: Unwittingly laying the foundations of modern chemistry, the alchemists of the Middle Ages sought in vain to turn ordinary metals into gold.

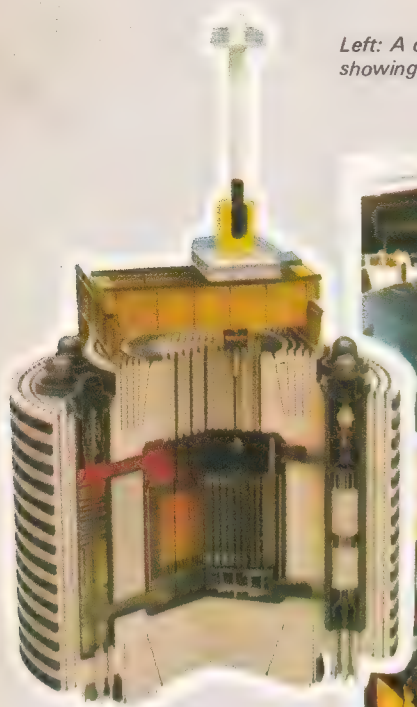
Right: Galileo with the telescopes that provided the evidence to prove Copernicus right.

Below: A copy of George Graham's orrery (1713) a clever mechanical model of the universe.

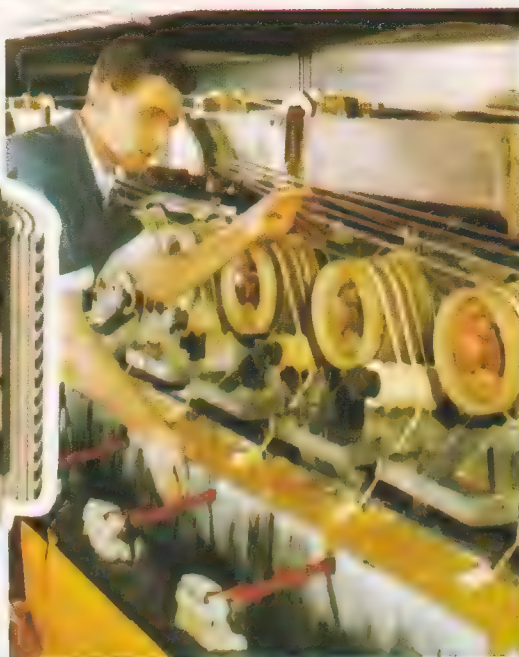
Bottom: Risking his life. Benjamin Franklin demonstrates that lightning is an electrical discharge with the aid of a kite, a wet string and a key.



Left: A cutaway model of a nuclear reactor core showing the arrangement of the moderator rods.



Right: Filaments of viscose rayon, a modern textile fibre, being treated in an acid bath.



Above: Modern technology has made it possible to drill for oil under the sea.

Right: The lunar module of one of the Apollo space missions to the moon. The Earth can be seen in the background.



known, it was possible for one man to have a grasp of all the current knowledge in quite a broad field. But in the 1800s so many advances were made that science became the dedicated study of professionals in ever-narrowing fields.

During the 1700s great advances were made in chemistry and biology. For example, several new chemical elements were discovered, and Carolus Linnaeus developed the method of naming plants and animals that is still in use today.

In the 1800s several scientists, such as Hans Oersted and Michael Faraday, made progress in the study of electricity and magnetism. At the same time, the chemist Dmitri Mendeleev worked out his Periodic Table of the Elements, and John Dalton developed his atomic theory. Discoveries were also being made in biology. Charles Darwin presented his idea of the evolution of living things, and Gregor Mendel discovered the basic laws of genetics.

The 1900s have seen by far the most rapid increase in scientific knowledge. The most dramatic advance has been the result of atomic research. Newton's ideas of the universe were shown to be inaccurate, and in 1900 Max Planck put forward his quantum theory. Albert Einstein extended this theory a few years later, and went on to publish his famous Special Theory of Relativity. Dalton's atomic theory had suggested that atoms were the smallest particles that could exist. But in the early 1900s research by Ernest Rutherford and Neils Bohr led to the discovery of smaller particles within the atom — electrons, protons and neutrons. Today, atomic researchers are still discovering even smaller particles than these.

In biology, progress has been made in the study of all aspects of the human body, and the research field that is now of greatest importance is that of molecular biology. The discovery of the structure of the DNA molecule by James Watson and Francis Crick has given biologists a much greater understanding of how characteristics are passed from one generation to another.

Modern scientific advances have led to similar progress in technology. The chemical industry now produces many new compounds including plastics, synthetic fibres and medicines. One of the most spectacular achievements of technology has been space travel. The first artificial satellites were sent up in 1958, and the first manned space flight occurred in 1961.

Science is still progressing rapidly, but there are still many problems to be solved. Astronomers have not yet come up with a satisfactory explanation of the origin of the universe. Medical scientists are not yet able to cure cancer or the various virus diseases. But research is being carried out all the time, and whatever the subject of study, the method of the scientist is unchanging: the observation and classification of facts, and finding their place in the order of nature.

The Nature of Matter

The alchemists of the Middle Ages tried to change the nature of matter, endeavouring to convert ordinary metals into gold by a mixture of science and magic. They were unsuccessful, but today's nuclear physicists have delved into the innermost secrets of nature and have discovered the fundamental building blocks of which everything is made. Knowing the nature of matter, changing it is to them a simple task.



Left: Atoms are so small that if an atom were the size of your little finger nail, then your hand would be large enough to grasp the Earth!



But just as splitting up the books in a library would destroy the library and tearing the pages out of a book would destroy the book, so separating a paper molecule into its atoms would destroy its identity. We would not have paper any more but merely a random group of atoms.

We can therefore say that everything is made of molecules, because a molecule is the smallest part of a substance that still retains the identity of the substance. The molecules of a particular substance—paper, skin, water, sugar—all are exactly the same and are different from the molecules of all other substances. Every molecule of a substance is made up of the same number of atoms linked together in exactly the same pattern. Another substance may have molecules of the same atoms arranged in a different pattern and it would be completely different. There are therefore as many different molecules as there are different substances, but the number of different atoms is very much smaller. At present, 106 different kinds of atoms are known and everything in the Universe is made up of combinations of these atoms. All atoms are about the same size—a hundred-millionth of a centimetre across. This means that this page is about two million atoms thick.

Any substance which is made up of molecules containing the same kind of atoms is called an *element*. The number of different elements is therefore also 106, although less than a hundred are found in nature and the others are made artificially. The commonest elements on Earth are oxygen and hydrogen, which together make up water, and sodium and chlorine, which together make up salt. The reason for this is that the most abundant substance on Earth is the salty water of the oceans. We could also say that everything is

Atoms & Elements

Have you ever thought what things are made of? Take this book, for example. You have probably taken it down from a shelf in a bookcase or a library. The library is made up of a collection of books, and each book is a collection of pages. The paper of each page is a collection of paper fibres pressed together. Can we go on dividing in this way and find out what the fibres consist of? The answer is yes, but the next step takes us into a realm of things so small they are invisible except in the most powerful microscopes.

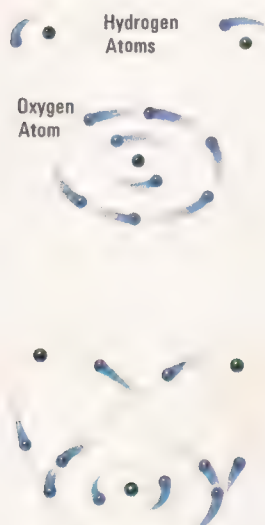
The paper fibres are made up of collections of tiny particles called *molecules*, and there are about 100,000 molecules in the thickness of this page. At this point, we must stop. We could go on dividing, because molecules are made up of smaller particles called atoms.

Right: A chain of thorium atoms photographed with a special high-power microscope. Each white dot is one atom. Thorium is a heavy, radioactive metal.





Salt (sodium chloride) is an ionic compound made up of sodium and chlorine ions. When it forms, each sodium atom loses one of its outer electrons, which goes to a chlorine atom. An ionic bond forms as the negative chlorine ion is attracted to the positive sodium ion.



Above: Water (hydrogen oxide) is a covalent compound made up of hydrogen and oxygen. Two hydrogen atoms join with one oxygen atom to make up a molecule of water. A covalent bond forms between each hydrogen atom and the oxygen atom. The hydrogen atom gives its single electron and the oxygen atom one of its outer electrons to form the bond, and the shared electrons move around both atoms. Outer shells of two or eight electrons are often produced in bond formation, because they are very stable.

made up of elements, except that some substances are pure elements—gold or silver, for example. Many elements, especially metals, do not really contain molecules but are made up of single atoms grouped together. However, we do say that their molecules are *monatomic*—made up of single atoms.

Everything is therefore made up of molecules or in some cases atoms, but what lies between the molecules or between the atoms? The answer is nothing, except for invisible forces that link atoms to one another to form molecules and pull molecules together to give a substance a certain degree of solidity.

Elements in Partnership

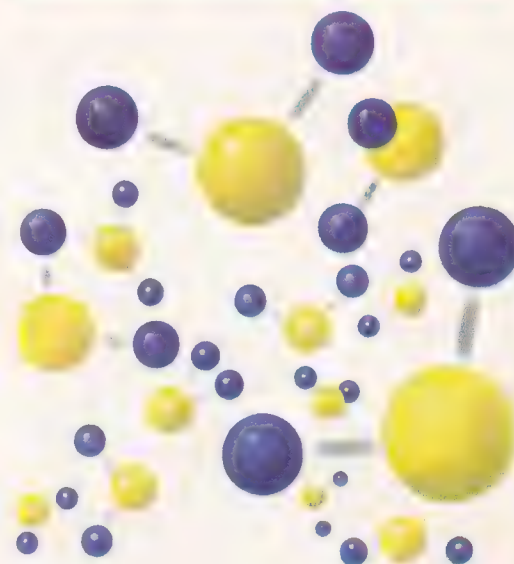
Any substance made up of two or more elements is called a *compound*: salt is a compound of sodium and chlorine; water is a compound of hydrogen and oxygen. Many substances are made up of mixtures of elements and/or compounds. Air is a mixture of two elements (oxygen and nitrogen) and salty water is a mixture of two compounds (salt and water). It is easy to separate mixtures into their constituents; salt will crystallize from a pool of sea water as water evaporates in the sun, and oxygen and nitrogen can be separated by liquefying air. But the elements in compounds are tightly bound by the forces between them; water and salt can only be split into their elements by forcing a powerful current of electricity through them.

There are basically two different kinds of compounds because atoms link to form compounds in two different ways. *Ionic compounds* are made up of regular arrays of atoms in which all the atoms are held together throughout the compound. In fact, it is rather difficult to talk of ionic compounds having molecules because the atoms do not form distinct groups. Instead, a molecule is usually considered to be a simple proportion of the atoms denoted by the chemical formula. As salt has the formula NaCl (Na for sodium, Cl for chlorine), a molecule is thought of as being composed of one atom of each element, although in fact each atom is linked to all its neighbours. The other group of compounds are *covalent compounds*. In these compounds, the atoms do form separate molecules. Water is covalent, each molecule having two hydrogen atoms (H) linked to an oxygen atom (O). Its formula is therefore H_2O .

The invisible forces that link atoms together to form arrays in ionic compounds and molecules in covalent compounds are electrical in nature. This is why electricity is required to split compounds into their elements. The outside of an atom is made of moving electric particles called electrons. When an ionic bond links two atoms, one gives an electron to the other. This action produces a difference of electric charge between the two atoms, and they are pulled and held together in a bond by electrical force. In covalent compounds, the atoms within a molecule share electrons instead of giving them to each other.

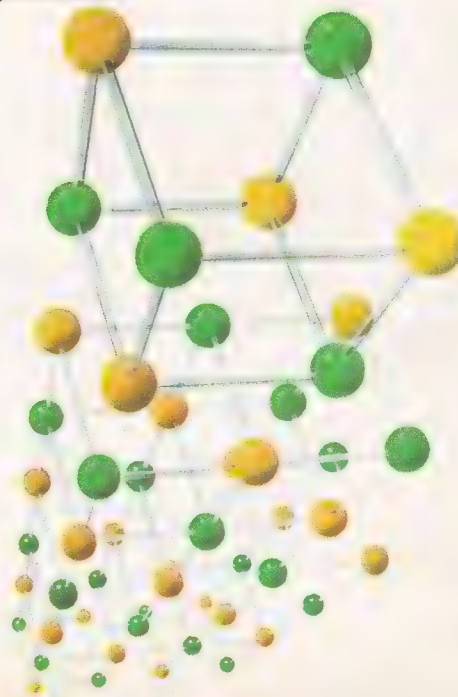
THE DISCOVERY OF ATOMS

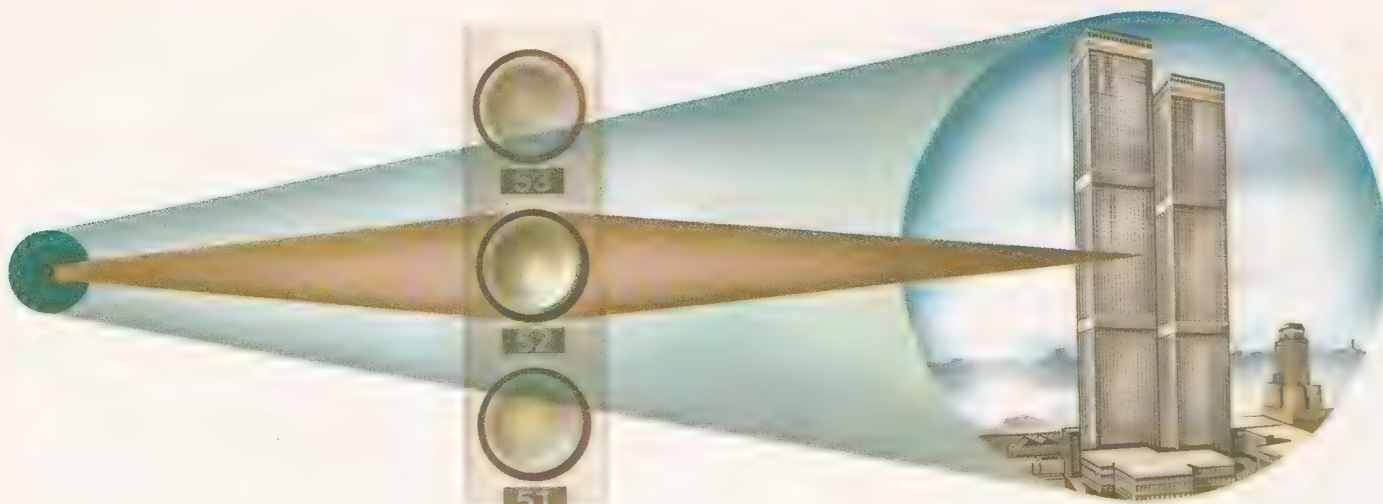
Atom is in fact a word coined by the ancient Greeks, and it means uncuttable or indivisible. A theory that everything is made up of tiny indivisible atoms was put forward by the Greek philosophers Leucippus and Democritus, who lived in the 400s BC, and developed by Epicurus a century later. They considered that only empty space exists between atoms, that atoms are in constant motion, and that atoms approach each other to form combined bodies. This theory was a remarkable prediction, but it was opposed by Aristotle, who believed that everything is made of four 'elements': earth, fire, air and water. Aristotle was so influential that it was more than two thousand years before atoms were re-discovered. The modern theory of atoms, which unlike Greek theory is based on scientific evidence, was founded by the British chemist John Dalton (1766–1844) in 1808. Three years later, the Italian scientist Amadeo Avogadro (1776–1856) put forward the concept of molecules.



Above: Water is made up of separate molecules. Each one consists of two hydrogen atoms (blue) joined to one oxygen atom (yellow) by covalent bonds.

Below: Salt (sodium chloride) is made up of sodium ions (green) and chlorine ions (yellow) all joined in a regular network.





Into the Atom

What does an atom look like? Pictures of atoms taken with the most powerful microscopes show only white blobs (see page 12). But even if it were possible to get more detailed pictures, there would be very little to see. Atoms are by no means solid, and in fact are composed almost entirely of empty space. The outside consists of *electrons*, tiny particles of electric charge, that are in constant motion. They move so fast that they form a cloud of electric charge at the boundary of the atom. This could be visible, because the electrons give out light as they jump from one orbit to another nearer the centre of the atom. The atom would probably look like a softly glowing ball.

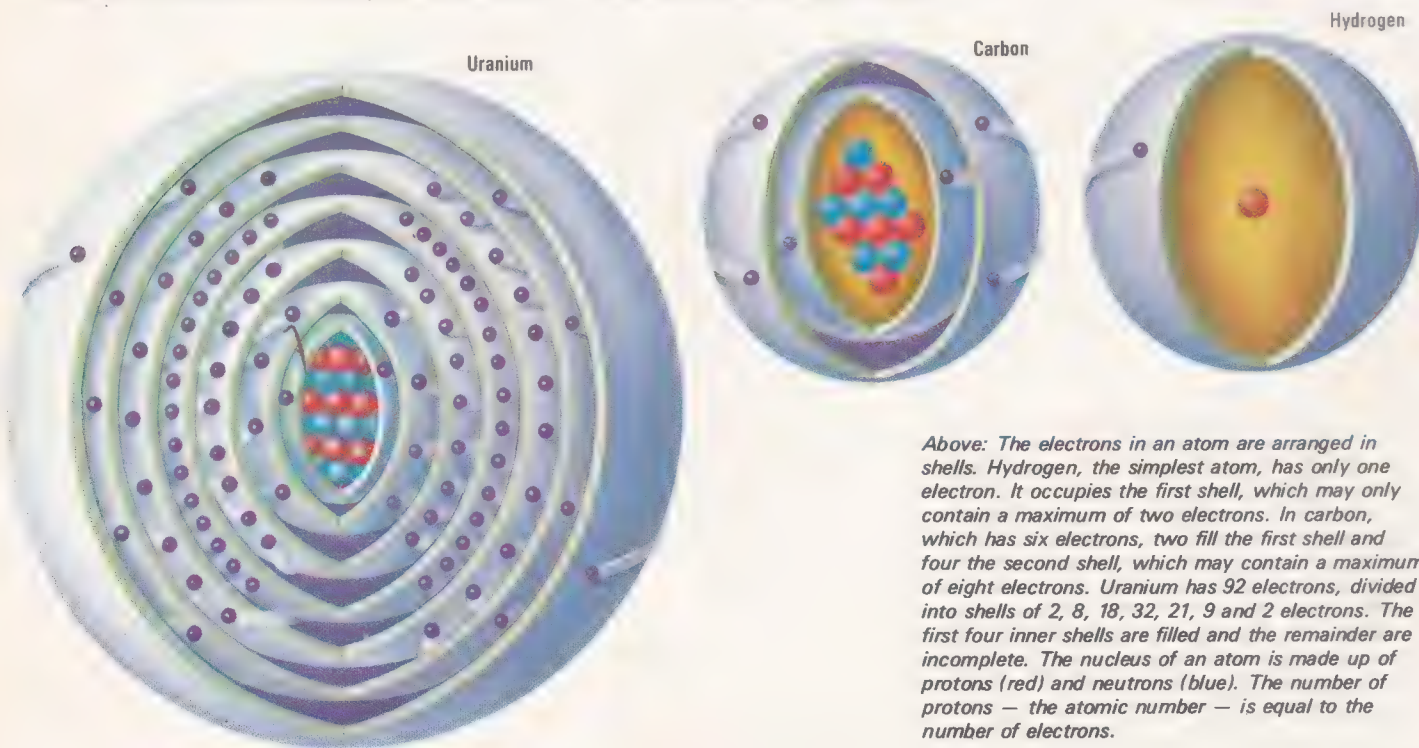
If we could penetrate the glowing sphere of charge, we would find empty space beneath until we reached the centre of the atom. There we would find a tiny body called the *nucleus* of the atom. It is only about one ten-

thousandth of the size of the atom. Yet, although it is so small, the nucleus is several thousand times as heavy as the electrons that move around it.

The nucleus and the electrons have different electric charges: the electrons are negative and the nucleus positive. In electricity, positive and negative charges attract each other, and the electrical attraction between the electrons and nucleus prevents the electrons from flying out away from the atom. The number of positive charges on the nucleus is equal to the number of electrons, which have one negative charge each so that the charges balance each other and the atom as a whole has no electric charge. However when bonds form, the atoms lose, gain or share electrons and take on electric charges that draw them together. But they cannot penetrate each other because the negative charge of the electron cloud around one atom repels the negative cloud around another.

Above: An atom is made up of a tiny central nucleus surrounded by electrons. The nucleus is so much smaller than the atom that if it were the size of a lift button, then the atom would be as big as a skyscraper.

Opposite below: A mass spectrometer identifies beams of atoms by bending them in magnetic and electric fields. Atoms of different masses are deflected by different amounts.



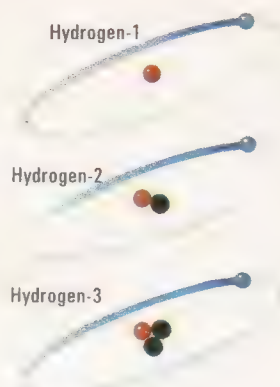
Above: The electrons in an atom are arranged in shells. Hydrogen, the simplest atom, has only one electron. It occupies the first shell, which may only contain a maximum of two electrons. In carbon, which has six electrons, two fill the first shell and four the second shell, which may contain a maximum of eight electrons. Uranium has 92 electrons, divided into shells of 2, 8, 18, 32, 21, 9 and 2 electrons. The first four inner shells are filled and the remainder are incomplete. The nucleus of an atom is made up of protons (red) and neutrons (blue). The number of protons — the atomic number — is equal to the number of electrons.

When an electric current flows through a metal, electrons wander among the atoms, producing a movement of electric charge. Rubbing a material can cause the electrons to become detached from their atoms, producing an electric charge on the material. Static electricity is produced in this way, from the small charge that makes a comb attract hair when combing in dry conditions to the great electric discharge that occurs in a flash of lightning.

Into The Nucleus

In our search to find the most basic particles of which all matter is made, we must now see whether the nucleus can be divided into any smaller particles. In fact it can, for the splitting of the atom that occurs in atomic energy production is really a fracture of the nucleus. This is why atomic energy is also known as nuclear energy. The nucleus is made up of two main particles packed tightly together; these are the *proton*, which has a single positive charge equal in strength to the negative charge of the electron, and the *neutron*, which has no charge. Both particles have about the same mass, being nearly 2000 times heavier than the electron. As the electric charges in an atom are balanced, the number of protons in the nucleus is equal to the number of electrons that orbit around it. Other kinds of particles also exist in the nucleus in addition to protons and neutrons, and as yet no particles smaller than these nuclear particles have been found. However, this does not mean that we have discovered the fundamental particles of which everything is made. Scientists expect some day to find even smaller particles within the nuclear particles.

The simplest atom is that of hydrogen, which consists of one electron orbiting a



The isotopes of an element differ from each other by the number of neutrons in the nucleus. Hydrogen (above) has three isotopes: the common isotope hydrogen-1, the rare isotope hydrogen-2, or deuterium, and an artificial isotope hydrogen-3, or tritium. In each case, one proton is present in the nucleus and one electron orbits the nucleus because the isotopes are of hydrogen. In the isotopes of helium (below), two electrons and two protons are present, and one or two neutrons, giving helium-3 and helium-4.



nucleus made up of one proton. The nuclei of all other atoms contain neutrons as well as protons. Carbon, for example, has a nucleus of six protons and six neutrons around which six electrons orbit. What difference then does the presence of neutrons make to an atom? The answer is very little. Having no charge, neutrons only increase the mass of the nucleus and several different forms of every element exist that contain different numbers of neutrons. These different forms are called *isotopes*. Chlorine gas occurs as a mixture of two isotopes, one containing 18 neutrons in the nucleus and the other 20 in addition to the 17 protons. The isotopes of an element are chemically identical and look alike. Their physical characteristics are slightly different. Usually, the presence of isotopes is of no importance but in nuclear physics, isotopes are very useful.

Sir Joseph John Thomson (1856–1940), a British physicist, showed in 1897 that cathode rays consist of beams of minute particles bearing negative electric charges. The particles were called electrons, a name that had already been put forward, but Thomson is considered to have discovered the electron.

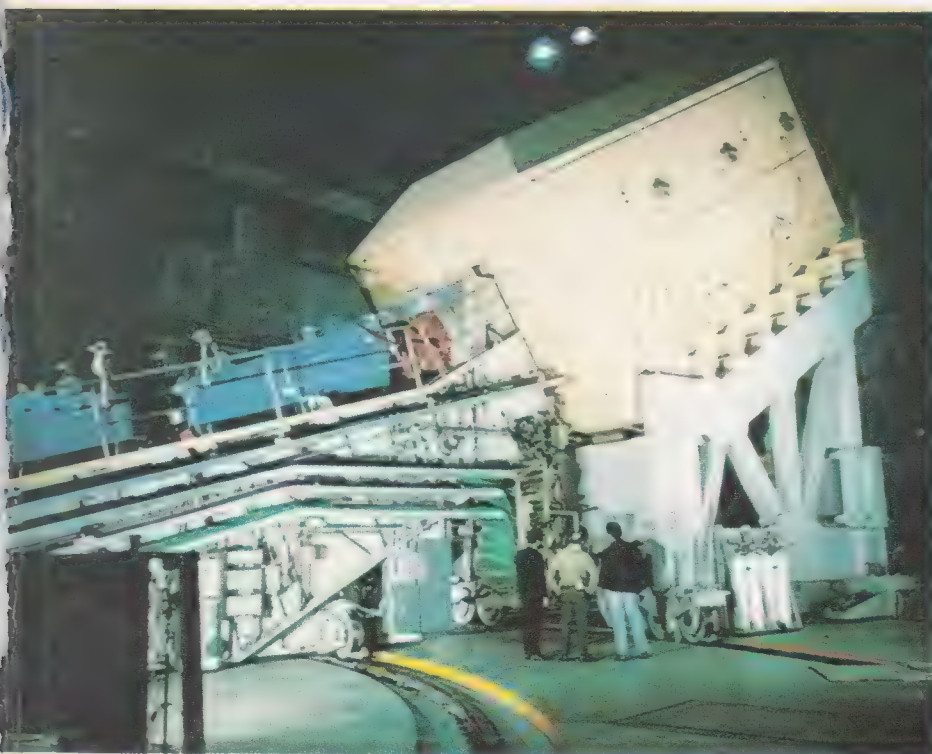
Ernest Rutherford (1871–1937) was born in New Zealand but worked in Britain and Canada. He studied under J. J. Thomson and became the first man to explain the structure of the atom in 1911. Earlier experiments by Rutherford had showed unexpectedly that alpha particles (positive particles) are scattered when fired through gold foil. Rutherford reasoned that a positive nucleus within the gold atoms deflects the particles. He concluded that the atom has a positive nucleus surrounded by negative electrons. Rutherford was later knighted.

The two men went on to make other important discoveries. In the same year as Rutherford announced his discovery of the nucleus, Thomson obtained the first indications that isotopes exist. Rutherford went on to split the atom.

Identifying Atoms

As the atoms of an element have a set number of protons and neutrons, we have a ready way of identifying them. The *atomic number* of an element is the number of protons in its nucleus; hydrogen has an atomic number of 1 and carbon 6, for example. The number of protons and neutrons is called the *mass number* and it identifies isotopes. The two chlorine isotopes mentioned above have mass numbers of 35 and 37 and so they are known as chlorine-35 and chlorine-37. Often the chemical symbol is used—Cl-35 and Cl-37, and sometimes the atomic number is added before the symbol— $^{17}_{35}\text{Cl}$ and $^{17}_{37}\text{Cl}$.

The *atomic weight* is completely different. This is a measure of the average weight of the atoms of an element as they occur in nature and it is compared to the isotope carbon-12, which is given an atomic weight of exactly 12. Atomic weights are not whole numbers because most naturally occurring elements contain several isotopes. Thus the atomic weight of chlorine is 35.453.





Above: Radioactive materials are handled by manipulators behind a screen that absorbs radiation. The manipulators work like hands and are capable of very delicate movements.

Unstable Atoms

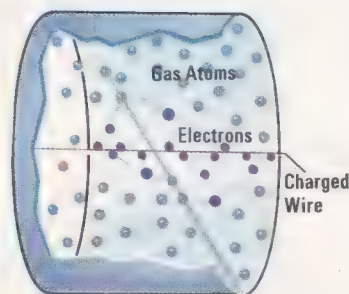
Phrases such as 'splitting the atom' and 'atom smashers' conjure up an impression of tremendous and perhaps terrible power. Great power is in fact often necessary to split the atom, and atom smashers, or particle accelerators as they are more correctly known, may be needed. Furthermore, the consequences have sometimes been terrible but a lot of good has also come from splitting the atom.

Splitting the atom really means breaking the nucleus apart, for electrons can be easily detached from their orbits around the nucleus without greatly changing an atom. If the nucleus should change in any way, the identity of the atom will change; that is, a new element will be formed. The nuclear physicist is therefore a modern alchemist, able to change one element into another as he pleases. The medieval alchemists toiled in vain for centuries in an effort to transmute

ordinary metals into gold. In fact, transmutation was going on around the alchemists but they did not know enough about the nature of matter to realize this. Some elements change spontaneously into others, and no power is required to make them change. They give out radiation as they do so and are therefore known as *radioactive* elements. The natural radioactive elements include uranium, thorium and radium.

Radioactivity

Radioactivity was discovered by accident in 1896, when a French physicist named Henri Becquerel (1852-1908) was looking for sources of X-rays. He placed a piece of uranium mineral on an unopened packet of photographic film and later found that the film was fogged. He realized that uranium must produce rays that can penetrate paper and fog photographic film. He found that the rays



Particle

have a negative electric charge. The French chemists Pierre Curie (1859–1906) and Marie Curie (1867–1934) and the British physicist Ernest Rutherford joined in the study of radioactivity, and two other kinds of radiations were found—rays with a positive charge and rays without any charge. Rutherford named the positive rays *alpha rays*, the negative rays *beta rays*, and the uncharged rays *gamma rays*, after the first three letters of the Greek alphabet. Sometimes the Greek letters themselves are used.

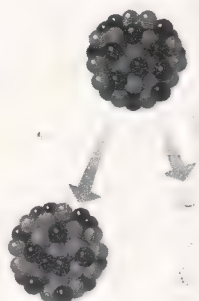
Rutherford later proved that alpha rays (α rays) are made up of streams of particles that each consist of the nucleus of a helium atom. An alpha particle is therefore made up of two protons and two neutrons. Becquerel found that beta rays (β rays) consist of electrons, but electrons emitted from atoms are usually called beta particles. Rutherford showed that gamma rays (γ rays) are not made up of beams of particles, but are like powerful X-rays.

The three kinds of radiation vary greatly in penetrating power. Alpha rays can be stopped by a piece of paper, whereas beta rays will penetrate paper and can only be stopped by a thin sheet of metal. Gamma rays are extremely penetrating and will pass through a block of iron 30 cm wide. Thick shielding of lead or concrete is required to stop gamma rays. All the radiations are harmful to life because they disrupt atoms when they strike them, but gamma rays are the most deadly because they penetrate deep into the body.

However, the amount of radioactivity produced in nature is very small and does not harm us. Although the radioactive elements themselves are highly radioactive, they are rare and thinly spread in rocks. Radioactive minerals can be found by using radiation counters such as the geiger counter to detect their radioactivity. These detectors are called counters because they count the number of



Above: An alpha particle is emitted from the nucleus of an atom. It consists of two protons and two neutrons, and is in fact the nucleus of a helium atom.



Above: A beta particle, which is an electron, is emitted when a neutron in the nucleus changes into a proton and an electron.

Right: A prospector uses a radiation detector to find the tell-tale radiation that radioactive minerals produce. The radiation of the minerals is very weak and harmless because the radioactive elements they contain are present in low concentrations.



Left: A Geiger counter detects and records the number of radiation particles that pass through it. It contains a tube of gas with a central wire carrying a positive electric charge. As the particle passes through the gas, it knocks electrons from the atoms. The electrons travel to the wire and produce a signal that is recorded on a meter or as a click from a loudspeaker.

particles given off by a source of radioactivity. But the pure metals extracted from the minerals may be highly radioactive. The Curies investigated pitchblende, a uranium mineral, and found that it was much more radioactive than could be accounted for by the amount of uranium it contained. They suspected that an intensely radioactive element lay undiscovered within the pitchblende. They found it eventually, but the new element was so powerfully radioactive that the mineral contained only a minute trace of it. They laboured for four years to isolate it and from several tons of ore, they obtained only a tenth of a gram of the new element, which they called radium. It is so radioactive that it glows in the dark.

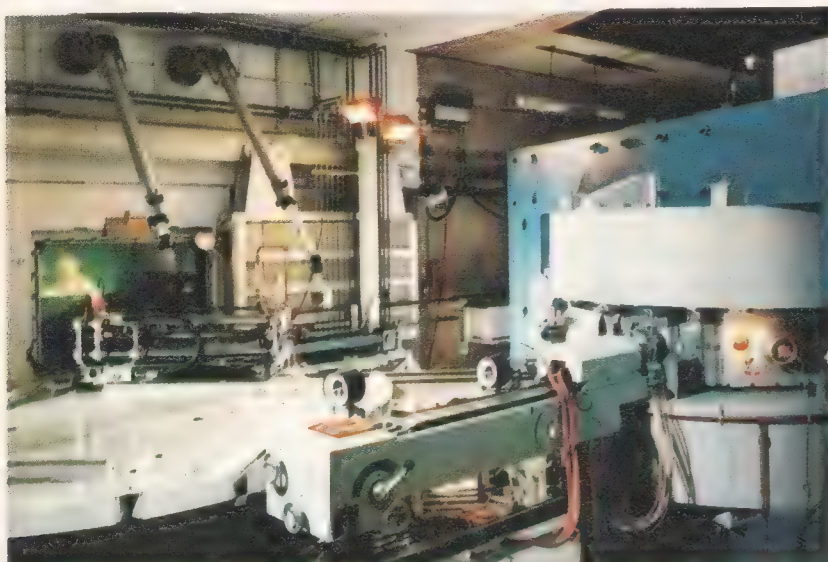
Handling Radiation

The Curies did not realize it, but they were dicing with death as they handled radium and other radioactive materials. Pierre Curie found that radium easily burns the skin, but neither knew that the radiation was tearing apart the atoms in their bodies. Pierre died in a street accident, but Marie and their daughter both died of leukemia, a blood disease that has since been associated with radiation.

People who handle radioactive materials therefore take no chances with radiation. All machines and containers that house the materials are heavily shielded to prevent radiation getting out, and are carefully sealed to make sure that no radioactive material escapes. The materials are handled either automatically or by remote controllers that work like mechanical hands. Workers that do have to enter radioactive areas wear special plastic suits with their own air supply. After use, the suits are washed down to remove any contamination and the workers are checked with radiation counters. All the staff in a nuclear establishment wear film badges—a small piece of film inside a plastic holder. The pieces of film are developed regularly and if the wearer has been exposed to any radiation, the film will show how much has been absorbed. This may seem too late, but the body will tolerate a small amount of radiation. Using film badges and other radiation detectors ensures that this limit is not reached.

Modern Alchemy

Any radioactive change produces either alpha particles or beta particles, and gamma rays may be emitted as well. The radiation comes from the nucleus but in doing so, the nucleus loses particles and changes into the nucleus of another element. When an alpha particle is emitted, the nucleus loses two protons and two neutrons. Its atomic number falls by two and its mass number by four. For example, the common isotope of uranium (atomic number 92) is uranium-238. It undergoes radioactive decay by emitting alpha particles and becomes thorium-234, an isotope of thorium (atomic number 90). The emission



Left: A radioisotope (radioactive isotope) is made by placing a sample of a non-radioactive element in a cyclotron and bombarding it with atomic particles. The operation is carried out by manipulators as the radiation produced is dangerous.

of a beta particle is the same as losing an electron; although the nucleus does not contain electrons, a neutron can be considered a combination of a proton and electron. In beta emission, a neutron changes into a proton and an electron is produced. The atomic number increases by one but the mass number remains the same. Potassium-40, a natural radioactive isotope of potassium (atomic number 19) emits beta rays and becomes calcium-40, the common isotope of calcium (atomic number 20).

Half of Half of Half of . . .

If radioactive elements are always changing into other elements, how is it that there are any left on the Earth? The answer is that some of the elements change very slowly, although many elements that decay rapidly have disappeared and now can only be made artificially. The rate of radioactive change is measured by the *half-life* of an isotope. This is the time it takes for half of any amount of the element to undergo radioactive change. Over the next half-life period, half of what is left (a quarter of the original amount) will decay, and then half of this half (an eighth) and so on. This process will continue inevitably—for nothing can stop radioactive decay—until the very last atom changes. Half-lives vary greatly. Uranium-238 has a half-life of 4510 million years. This is about the same as the age of the Earth, and it means that about half of all the uranium in the world has vanished by natural radioactivity since the Earth was formed about 4600 million years ago.

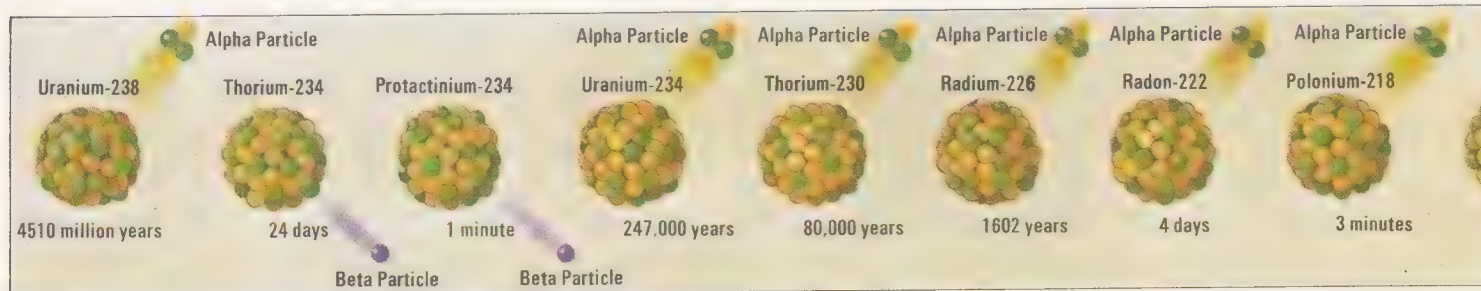


Above: The half-life of a radioisotope is the time it takes for half of any amount of it to change into another isotope. If we had a block of iodine-128, which has a half-life of 25 minutes, half of it would disappear every 25 minutes as it changed into xenon-128, a gas.

one has a half-life of nearly a millionth of a second! The series includes the intensely radioactive metal radium-226, which is comparatively long-lived with a half-life of 1602 years. Radium and the other members of the series are always to be found because as each decays, more is being formed by the previous member in the series. They will continue to exist in nature until all the first member—uranium-238—has entirely decayed.

Two other natural radioactive series exist, starting with uranium-235 and thorium-232 and ending with lead-207 and lead-208 respectively. Four series are possible in all (because alpha decay reduces the mass number by four), and a fourth series would have plutonium-241 as its parent isotope. However, no isotope in this series has a half-life greater than two million years and they have all long

Below: The radioactive series that begins with uranium-238 and ends with lead-206. The half-life of each change is given.

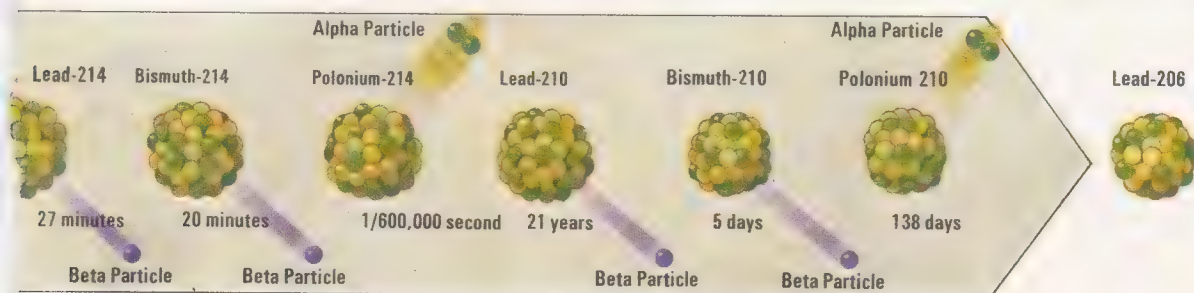


since decayed into its final member—bismuth-209. In fact, this isotope is weakly radioactive but its half-life is about 100,000 million million years, so very little will have decayed in the Earth's lifetime.

Radioactive Dating

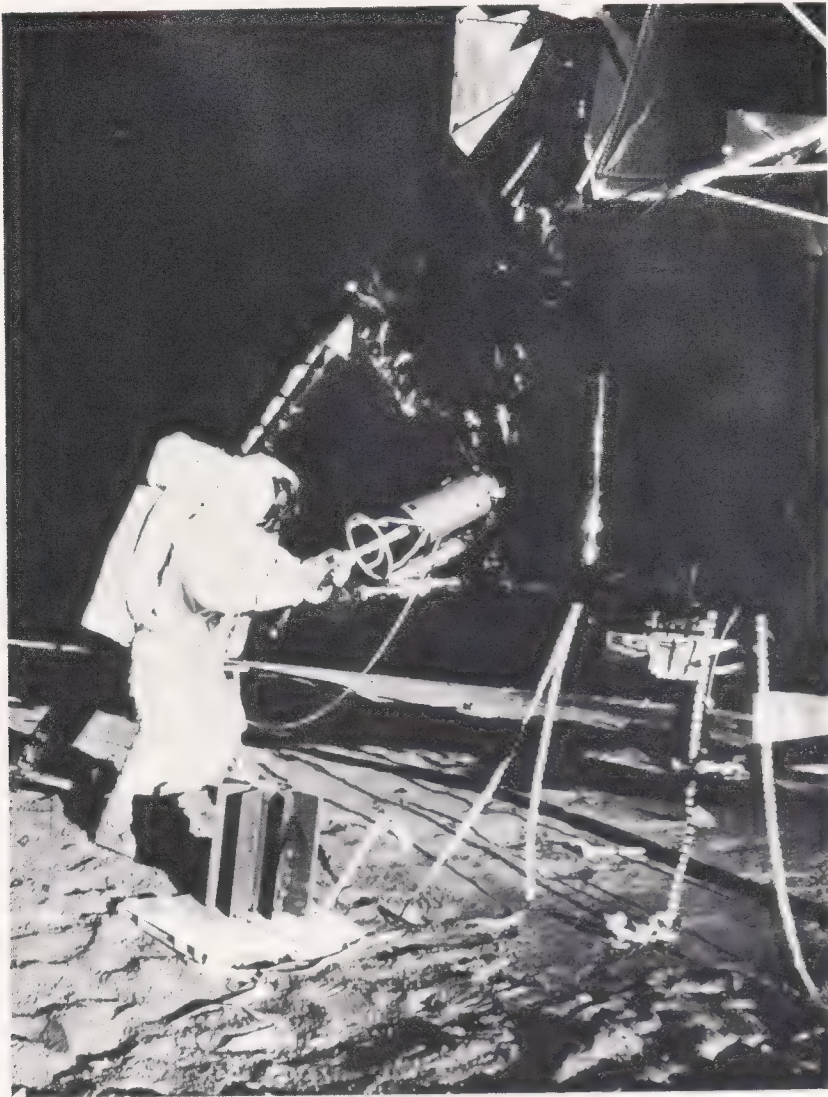
The elements in the radioactive series do not complete the number of radioactive elements that occur naturally on the Earth. As cosmic rays strike the Earth, they collide with atoms and change them into other radioactive isotopes. A small amount of the nitrogen in the air is changed into radioactive carbon-14 and taken up by living things. This means that you yourself are slightly radioactive, though not enough to cause any harm. The proportion of carbon-14 in any living thing is constant; as it decays, more enters the organism from the atmosphere. But when a living thing dies, it takes in no more carbon-14 and the small amount left decays. Measuring the radioactivity of the dead remains of any living thing—a bone, a piece of wood, a shell—therefore gives a measure of its age. If its radioactivity is only half that of a living thing, then half of its carbon-14 will have gone. As the half-life of carbon-14 is 5570 years, this will be its age. If it is only a quarter as radioactive, two half-life periods will have passed and it will be 11,140 years old. *Radiocarbon dating*, as the method is called, can be used to estimate the ages of remains up to about 40,000 years old. For example, radiocarbon dating of human remains from pits at Stonehenge suggest that the site was first used as a temple in about 2200 BC. But the monument probably did not achieve its present form until much later, for a pick made from a deer antler which is thought to have been used in erecting the great stone arches is about 500 years younger. Radiocarbon dating assumes that the rate of production of carbon-14 in the atmosphere has always been constant, but this may not be so and fluctuations may have occurred. However, as these come to light, they can be allowed for, and radiocarbon dating remains a good method of finding the ages of remains.

Rocks can also be dated by radioactive methods. The proportion of lead isotopes resulting from the decay of uranium through the radioactive series gives an estimate of the ages of the oldest rocks. This method gives an age of 4600 million years for both the Moon and meteorites, and the Earth is thought to have the same age.



Above: Fossils of a crinoid or sea lily and two coral colonies embedded in a slab of limestone. These primitive animals lived about 300 million years ago. Radioactive dating has enabled scientists to find the ages of remains.

Harnessing Radioactivity



Above: An astronaut on the Moon takes a canister of a radioisotope from his spacecraft. The isotope produces heat. When placed in the generator at his feet, electricity is produced to power the scientific instruments left on the Moon.



Above: An aircraft engine is examined by passing gamma rays from a radioisotope (left) through the engine wall to photographic films placed on the outside.

The penetrating radiations of radioactive isotopes give us a way of looking into things such as metal objects, sealed containers and even the human body, without having to cut them open. Their effects on living things may also be of use to us. In all cases, the amount of radiation must be carefully controlled and many different radioisotopes are manufactured to give a wide range of irradiating power.

Radioisotopes are made from common non-radioactive isotopes by transforming them in machines that produce nuclear particles. Charged particles such as protons and alpha particles are produced in powerful beams by the cyclotron and other particle accelerators (see pages 22-3). Floods of neutrons, which being uncharged cannot be accelerated into beams, are produced in nuclear reactors (see page 30). As the particles strike the nuclei of elements placed in the machines, they change them into radioisotopes. For example, normal cobalt (cobalt-59) becomes the radioisotope cobalt-60 as it is struck by neutrons and each nucleus absorbs one neutron. Placing sulphur-32, the common isotope of sulphur (atomic number 16), in a nuclear reactor gives the radioisotope phosphorus-32. The absorption of a neutron causes the rejection of a proton, leaving the mass number the same but lowering the atomic number by one to 15, that of phosphorus.

Radioisotopes also come from the radioactive waste produced by nuclear reactors, in which heavy nuclei undergo fission and break apart into smaller nuclei. Among these fission products are the important radioisotopes strontium-90 and caesium-137.

Using Radioisotopes

The world of nuclear physics must seem a remote and distant one to most people, but in the uses of radioisotopes it comes close to everyone. In fact, you probably have a very small amount of radioisotope on your person right now. If you have a watch and it has a luminous dial so that you can read the time in the dark, then you are making use of radioisotopes. The luminous paint contains a very small amount of radioisotope—often radium-226—that produces alpha particles and causes the luminous chemicals in the paint to glow. The alpha particles cannot penetrate the metal back and glass face of the watch, and so you are perfectly safe.

Even though radiation can harm the human body, some of the most important



Left: A miniature electric battery powered by the radioisotope plutonium-238. The isotope produces heat as it decays and the heat powers a tiny generator. There is no radiation danger and the battery lasts for ten years. It can be used to power pacemakers, which keep people with heart trouble alive. The pacemaker produces electric signals that keep the heart beating.

uses of radioisotopes are in medicine. They are particularly valuable in the diagnosis or detection of certain diseases. If a solution containing a small concentration of radioisotope is given to a patient, it will move through the body in the bloodstream. Its progress can be followed by the tell-tale radiation that it produces. Certain radioisotopes will concentrate in certain parts of the body, and enable physicians to study these parts without opening the body. For example, a tumour can show up when sensitive detectors make a radiation picture of the brain. In this way, abnormalities can be found that do not show up on X-ray pictures. This technique of following the trail of radiation given out by a radioisotope as it progresses through the body or any other system is called using a radioactive tracer.

Overdoses of radiation can cause severe illness and even death by radiation sickness, but the radioisotopes used as tracers do not produce enough radiation or remain long enough in the body to do any harm. However, large doses of radiation may be given to patients who have tumours. The radiation acts to kill the tumour without harming the surrounding tissue. Radioisotopes that concentrate in certain parts of the body may act to cure diseases affecting these parts. Iodine-131 can be given to treat conditions of the thyroid gland and phosphorus-32 to treat blood cancer. This kind of medicine is known as *radiotherapy*.

Isotopes on the Farm

Radioisotopes also have many uses in agriculture. The use of radioactive tracers has proved of great value in understanding how plants and animals live. By incorporating tracers in fertilizers and animal feed, it is possible to find out exactly how plants and animals use the various elements that they take in, and to produce better fertilizers and more nutritious feed.

Damage to crops by insects can be reduced by the use of radioisotopes. Killing the insects in a field of crops by radiation would be expensive and hazardous, but a little radiation is sufficient to sterilize the insects so that they cannot breed. The insects are captured from

the wild and reared artificially in large numbers, then sterilized by radiation and released. Many of the wild insects mate with them but no young are born and the population of insects falls in the area. When gathered, the crops may be treated with radiation to kill off any other pests, such as weevils in grain. The radiation given is not sufficient to make the food radioactive. Furthermore, treating the food with radiation often proves to be a way of preserving it and giving it longer storage life.

One danger of radiation is its effect on heredity; it can cause mutations to be born. However, plant breeders make use of radiation to produce mutations from seeds. Not all mutations are harmful, and exposure to radiation may speed the production of new and better varieties of crops.

Isotopes in Industry

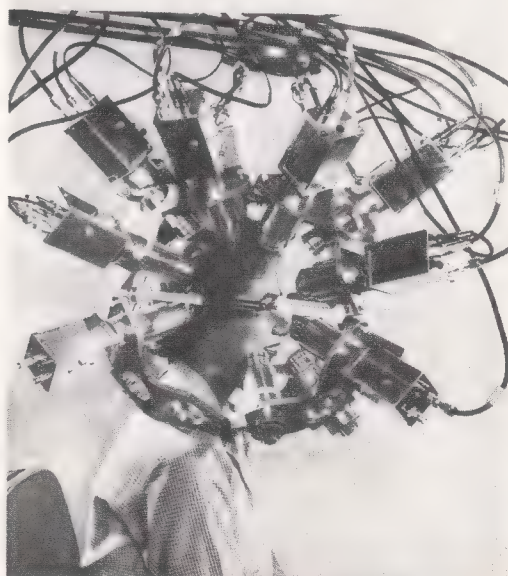
Industry also finds many uses for radioisotopes. Radiation can be passed through manufactured objects without making them radioactive. The radiation that emerges on the other side will show whether there are any flaws in the object. It will also show how thick the object is, and thickness gauges using radioisotopes are used in sheet metal rolling and many other manufacturing processes. The level of a liquid in a sealed container—from beer in a can to liquid metal in a furnace—can be checked in the same way. Leaks in pipelines can be quickly found by passing a radioisotope through the pipe; a radiation detector will easily locate the leak by the radiation it emits.

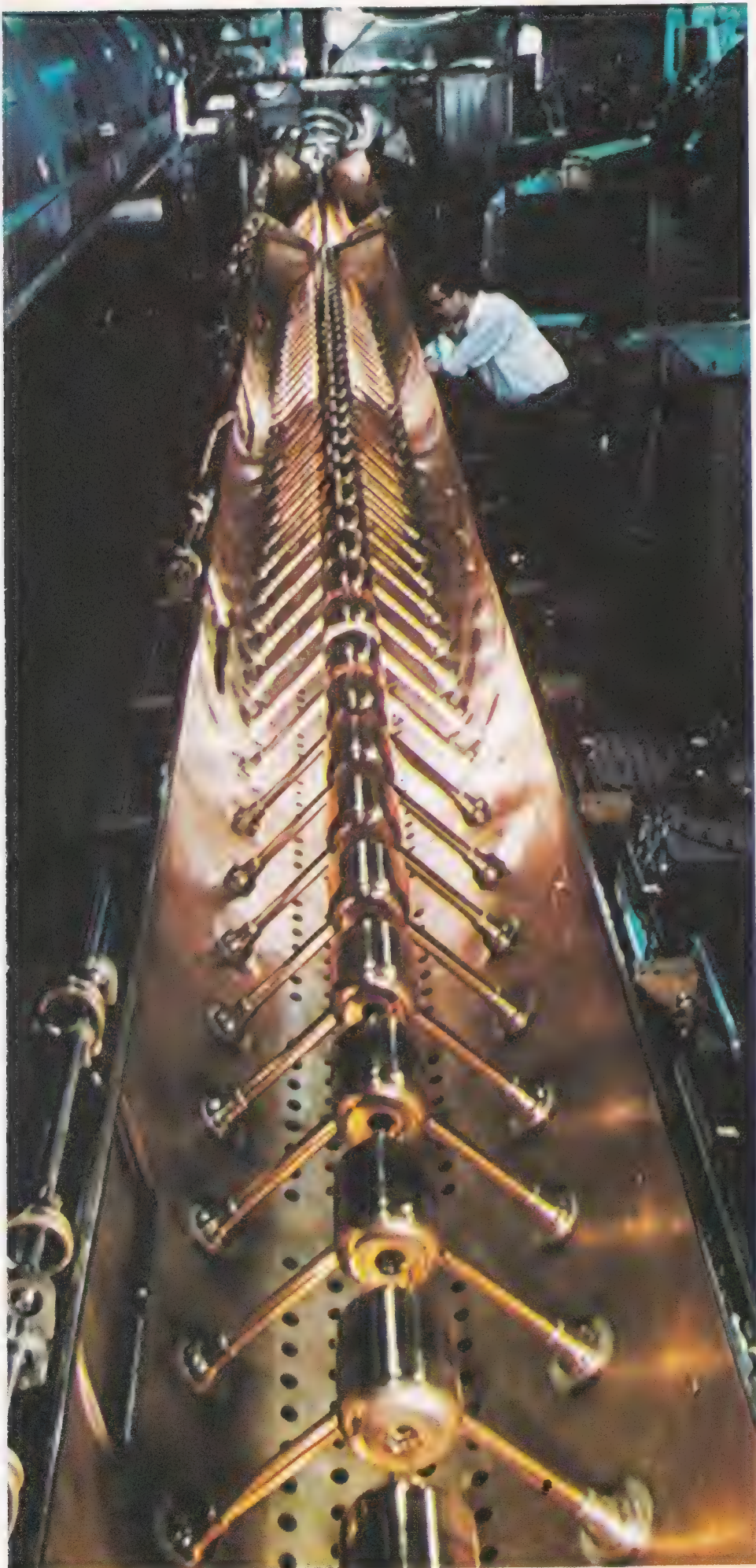
Neutron beams have similar uses to the radiations produced by radioisotopes. A neutron probe can detect the amount of water in soil from the slowing effect it has on neutrons, and indicate whether the ground needs irrigation. The neutrons are produced in the probe by using mixtures of radioisotopes, the production of particles by one causing neutron emission in the other.

Below: A telephone with a luminous dial can be used in the dark. It contains a very weak radioisotope and a phosphor that glows when struck by the radiation.

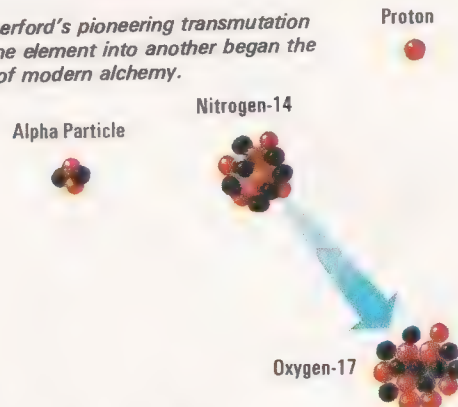


Right: A patient is given a sample of a radioisotope and surrounded by radiation detectors that can locate the position of a possible tumour in the brain. The isotope collects in any tumour and produces radiation that can be picked up by the detector.





Rutherford's pioneering transmutation of one element into another began the age of modern alchemy.



Modern Alchemy

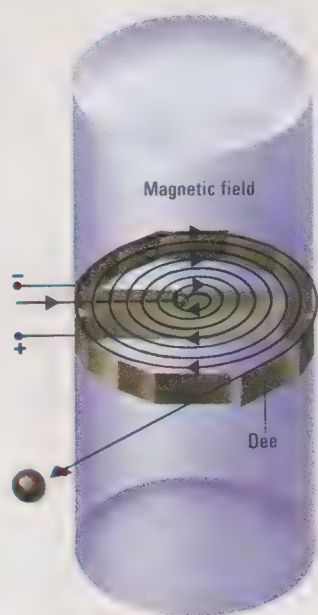
Lord Rutherford could be called the father of nuclear physics, for he made many pioneering discoveries as he delved further and further into the atom. But he is probably best known as the man who first transformed one element into another. In doing this, Rutherford became the first modern alchemist. In fact, Rutherford did not actually split an atom but built up a new one. He did this in basically the same way as radioisotopes are now produced, but he had no accelerators or reactors to produce beams of particles. Instead he used a natural source of particles—the alpha particles produced by a radioactive sample. In 1919, Rutherford found that the bombardment of alpha particles changes nitrogen-14 (the common isotope of nitrogen) into oxygen-17, a rare isotope of oxygen. A proton is emitted, the nitrogen nucleus taking up the remaining proton and two neutrons of the alpha particle.

More than a thousand different radioisotopes have since been produced, an average of about ten for every element. Some of these are elements that have probably vanished from the Earth by radioactive decay, but some are of entirely new elements. These man-made elements include all those greater in atomic number than uranium, such as neptunium and plutonium, and these are known as the *transuranic* elements.

After Rutherford had shown that elements could be transformed by bombarding them with particles, machines that could accelerate particles to high speeds and energies were required to explore this exciting new insight into nature. The first of these particle accelerators was invented in 1932 by the British physicist Sir John Cockcroft (1897–

Left: A view of a linear accelerator with its outer wall removed. Beams of particles are accelerated through the holes in the drift tubes.

PARTICLE ACCELERATORS

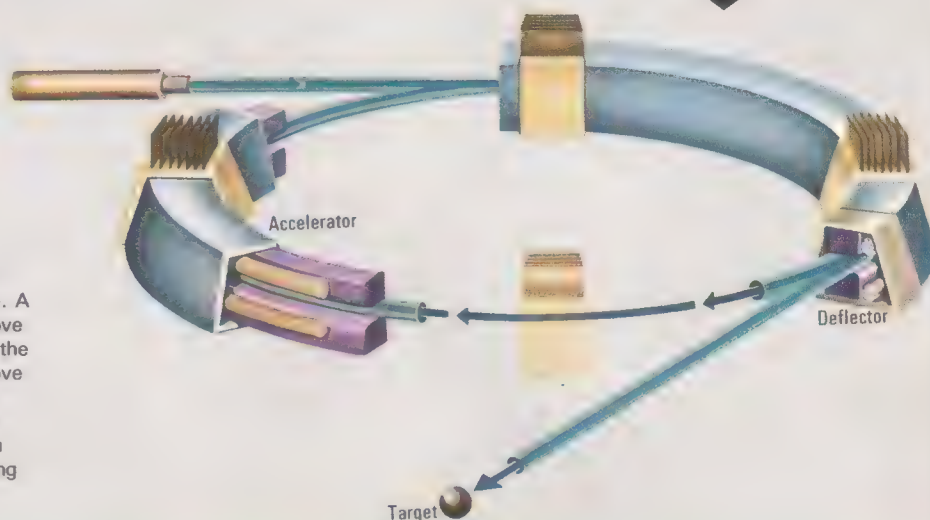


In A Cyclotron, the particles travel between dees (D-shaped plates) that are alternately charged positive and negative. A magnetic field produced by magnets above and below the plates curves the path of the particles, and as they speed up, they move outwards in a spiral. The deflector plate produces a strong electric charge to kick the beam from the cyclotron and strike a target. Radioisotopes are made by treating materials with particles beamed from cyclotrons.



In A Linear Accelerator, particles are sped by electric charges on the drift tubes. Each tube is alternately charged positive and negative so that each particle is pulled towards a tube and then pushed on its way as it leaves. The accelerated particles strike a target and a nuclear reaction takes place.

In A Synchrotron, the particles continually move in a circle and can be accelerated to very high energies. From the particle source, which is usually a linear accelerator, a beam of particles enters a circular tube surrounded by magnets. The particles travel around the tube many times, being accelerated by electric fields in the accelerating stations. As the particles get faster, the magnets increase their strength to hold the beam in the tube. Then the beam is deflected to strike a target.



Below: Scientists at work on a proton synchrotron. Beams of protons are accelerated in a tube within the curving line of magnets to the right. The beams leave the accelerator along the narrow tubes leading off to the left.

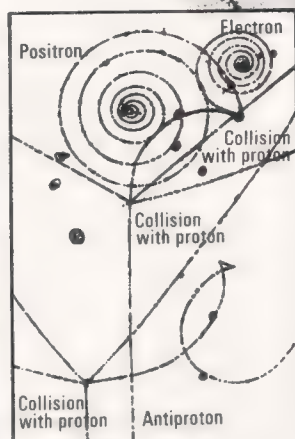


Above: The international radiation symbol. Radioactive areas and all containers of radioactive substances are marked with this symbol.



1967) and the Irish scientist Ernest Walton (1903–). It pushed the particles along an evacuated tube with a strong 'kick' of electric charge. The modern Van de Graaff generator works in the same way. These are low energy machines, and higher energies are achieved by giving the particles a series of 'kicks' as they move along the tube. The particles move in a straight line, and so these accelerators are called *linear accelerators*. It was soon realized that more energy could be given to particles if they could be made to move in a circle. The first circular accelerator was the *cyclotron*, developed by the American physicist Ernest Lawrence (1901–58) in the 1930s. In a cyclotron, the particles follow a spiral path, accelerating all the time until they leave the machine. Greater energies are achieved by keeping the particles to a circular path, which is done by increasing a magnetic field in the tube to prevent the particles spiralling outwards as they get faster. These machines are called *synchrotrons*. When the desired energy is achieved, the beam is deflected out of the machine. The most powerful accelerators are synchrotrons, the largest being two kilometres in diameter. It is at Weston, Illinois, in the United States. An even bigger machine is being built near Geneva, Switzerland by CERN, the European Organization for Nuclear Research.

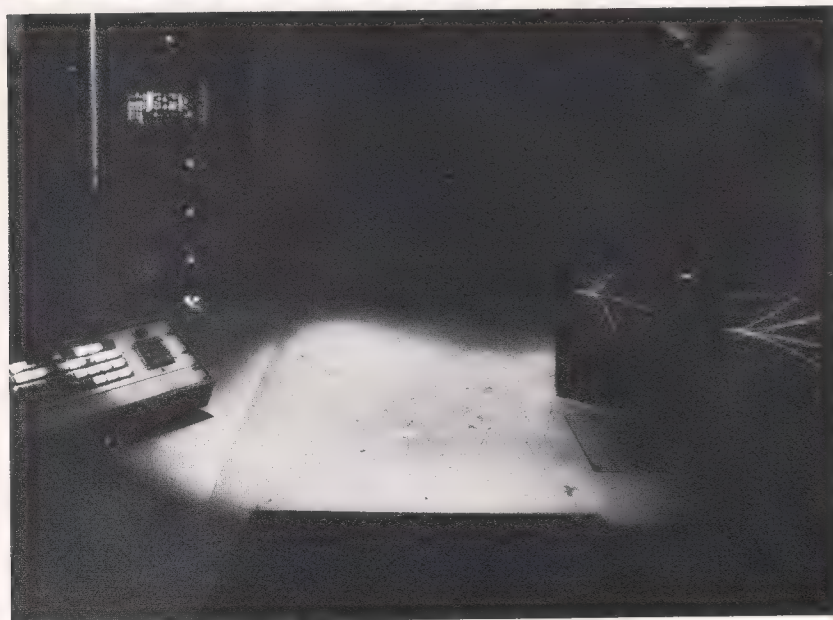
The Hunting of the Quark



Top: Tracks in a film show that a magnesium nucleus in a cosmic ray struck a bromine nucleus in the film, shattering both nuclei.

Above and left: Tracks in a hydrogen bubble chamber show the nuclear events produced by two antiprotons. Note that all the tracks are curved, but the faster particles curve less. The electron and positron, having opposite charges, curve in opposite directions.

Below: Analysis of bubble chamber photographs is carried out with the aid of a computer.



In 1932, the same year as the first particle accelerator—or 'atom smasher' as the machine came to be known—began to wreak havoc in the nucleus, the neutron was discovered by the British physicist Sir James Chadwick (1891–1974). It had been predicted by Rutherford as long before as 1920, and its discovery finally explained why isotopes exist. But one big question still lay unanswered: how does the nucleus hang together? Protons bear positive charges and, instead of being packed tightly together in the nucleus, they should fly apart from each other because like charges repel each other. The neutrons in the nucleus, being uncharged, could not stop them, so a strong force must exist in the nucleus to overcome the electrical forces and bind it together.

In 1935, a Japanese physicist named Hideki Yukawa (1907–) suggested that other particles—eventually called *mesons*—exist in the nucleus and hold it together. But to find them, they would somehow have to be knocked out of the nucleus. The only way to do this is to fire particles at the atom in the hope that a collision will break up the nucleus and produce new particles. This is rather like making two cars crash together and picking up the pieces to find out how the car is made, but it has opened up a new way into the innermost secrets of the atom.

Particle accelerators are the obvious way to explore the nucleus but the meson was eventually detected in another way. The discovery was made in 1947 by the British physicist Cecil Powell (1903–69)—not in a laboratory but high above the Earth. Cosmic rays consist of very energetic particles moving at sufficiently high speeds to shatter nuclei, but few penetrate the atmosphere and reach the ground. By flying packs of photographic emulsion beneath balloons, cosmic rays collide with nuclei in the emulsion and the fragments leave their identity in tracks through the pack. Powell found a track that could have only been made by a meson.

The development of particle accelerators since then has led to the discovery of many new particles. A beam of particles is fired from the accelerator at a target of some kind, and the nuclear fragments are detected in various ways. When charged particles graze atoms, they knock away outer electrons and ionize them; as a charged particle passes

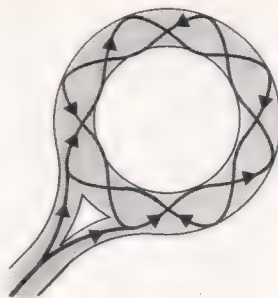
through a substance, it leaves a trail of ionization behind it. This trail can be viewed in a *bubble chamber*, which is a chamber containing liquid hydrogen or another liquid that is just about to boil. As the particle passes, it ionizes atoms in the liquid and leaves a momentary trail of bubbles behind it. This trail is photographed before it disappears. A magnetic field is applied to the chamber so that the path of the particle is curved. From the shape of the path, the mass and charge of the particle can be found. Uncharged particles and gamma rays leave no trail, but their existence can be deduced from the shapes of other tracks. Other detectors can also make ionization trails visible. The *cloud chamber* contains a vapour that condenses into a trail of droplets as the particle passes. In the *spark chamber*, moving particles leave trails of sparks behind them. Photographs of the trails are then analysed by computer.

Physicists expected the accelerator to produce a few fundamental particles that would simply explain the basic make-up of matter, but in fact a bewildering array of particles turned up. These are divided into several groups according to their properties.

The lightest particles are called *leptons* and they interact with each other weakly. They include the electron and the neutrino, a strange particle with no mass when it is at rest that is capable of passing right through the Earth. The heavier particles interact strongly and they are called *hadrons*. Within the hadrons are the mesons and hyperons, both identified by Greek letters, and the proton and neutron. Most particles live only a minute fraction of a second away from the nucleus. The proton and the electron are stable—they do not change. The neutron has a lifetime of a thousand seconds away from the nucleus, forming a proton, electron and an antineutrino.

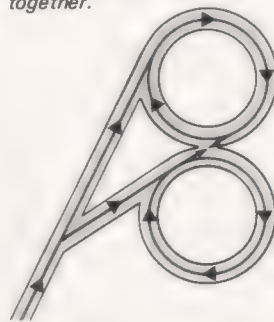
The antineutrino is an *antiparticle* to the neutrino. Every particle has its antiparticle in which its electric charge and other properties are reversed. For example, the antiparticle to the electron has a positive charge instead of a negative charge. It is known as the positron as well as an antielectron. Antiparticles have only been detected in nuclear events. However, antimatter could in theory exist in which atoms were made up of antiparticles instead of ordinary particles. Anti-hydrogen would have atoms each consisting of a positron orbiting an antiproton. Whenever an antiparticle meets its opposite normal particle, the two destroy each other in a burst of radiation. If antimatter were therefore to meet normal matter, there would be a tremendous explosion. It does not seem that antimatter can exist on Earth, but it may exist far away in outer space.

In 1964, physicists thought they had found underlying order in nuclear particles. Tables were constructed like the periodic table of the elements, and from a gap in one table the existence and properties of an unknown

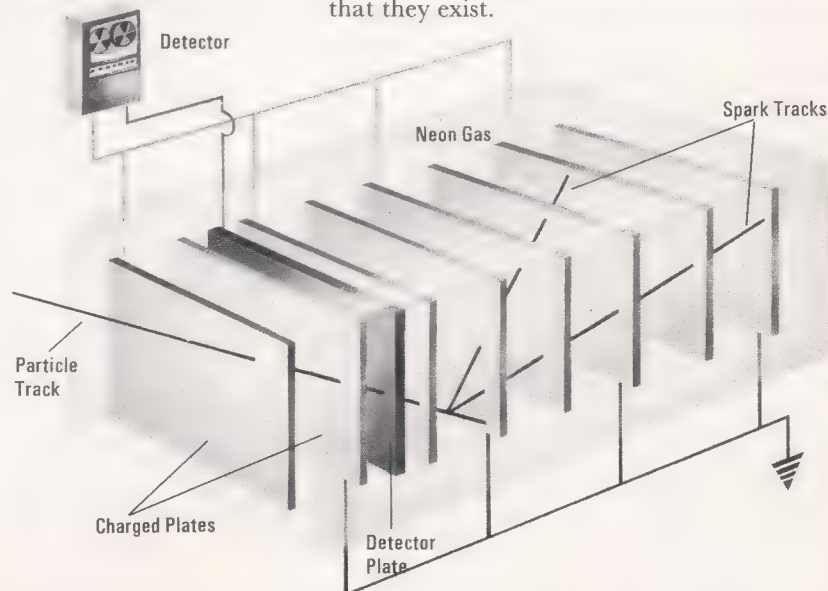


Above: Particle beams from an accelerator can circulate along winding paths in opposite directions in a storage ring, and then meet head-on to produce collisions of very high energy.

Below: Two separate storage rings may be used to store the particle beams before bringing them together.



Below: A spark chamber is used to detect and examine atomic particles. When a particle enters the chamber it passes through the detector plate. The detector then charges the other plates and the particle leaves a trail of red sparks in the neon gas inside the chamber.



PRINCIPAL ELEMENTARY PARTICLES (excluding antiparticles)

name	charge	mass compared with electron	lifetime (seconds)
Proton	+	1836	stable
Neutron	none	1838	1010
HYPERONS			
Xi-zero	none	2570	2.9×10^{-10}
Xi-minus	-	2580	1.7×10^{-10}
Sigma-plus	+	2320	8.1×10^{-11}
Sigma-zero	none	2330	less than 10^{-14}
Sigma-minus	-	2340	1.66×10^{-10}
Lambda	none	2160	2.5×10^{-10}
Omega-minus	-	3280	1.1×10^{-10}
LEPTONS			
Electron	-	1	stable
Neutrino	none	0	stable
Muon	-	207	2.2×10^{-6}
MESONS			
Eta	none	1070	unknown
K1-zero	none	970	10^{-10}
K2-zero	none	970	2.8×10^{-8}
K-minus	-	960	1.2×10^{-8}
K-plus	+	960	1.2×10^{-8}
Pi-plus	+	273	2.6×10^{-8}
Pi-zero	none	264	10^{-16}
Pi-minus	-	273	2.6×10^{-8}

particle were predicted. It was found in 1964 and named the omega-minus. On the basis of these tables of particles, it looks as if all particles could be composed of various combinations of just three smaller particles known as *quarks*, which would have two-thirds or one-third the charge of the electron. Quark is a word that comes from a line in *Finnegan's Wake* by James Joyce—'Three quarks for Muster Mark'. Nuclear physicists have therefore set to with vigour to find a quark, but so far have been unsuccessful. Perhaps this fundamental building block of matter will turn up. So too may other postulated particles—the faster-than-light tachyon and the magnetic monopole, a single pole of a magnet. They all disobey the laws of physics, but physicists would be delighted to detect them and reframe their laws. Reports of their existence have been made, but there is no conclusive evidence that they exist.



Nuclear Power

Hidden away inside the nucleus lies a vast storehouse of energy that man has only recently begun to tap. The releasing of this energy has given us power on a scale that no one would have thought possible. But, like all scientific discoveries, atomic energy or nuclear power can be used for evil as well as good. While many millions have benefited from nuclear power, many thousands have been killed by it and it could possibly destroy all life on our planet.

Nuclear power had its beginnings in 1934. Physicists had started to bombard all kinds of atoms with all kinds of particles to see what would happen. Enrico Fermi (1901–54), an Italian physicist, tried firing neutrons at uranium atoms in an effort to make an element heavier than uranium. His results were confusing because, as was later shown in Germany, when an atom of the rare uranium isotope, uranium-235, absorbs a neutron, it breaks apart into two smaller nuclei and gives out two or three neutrons. This process is called *nuclear fission*, and the nuclei and particles produced move out at great speed, causing much heat to be developed.

These were the turbulent years before World War II and the discovery of fission—one of the most important ever made—occurred



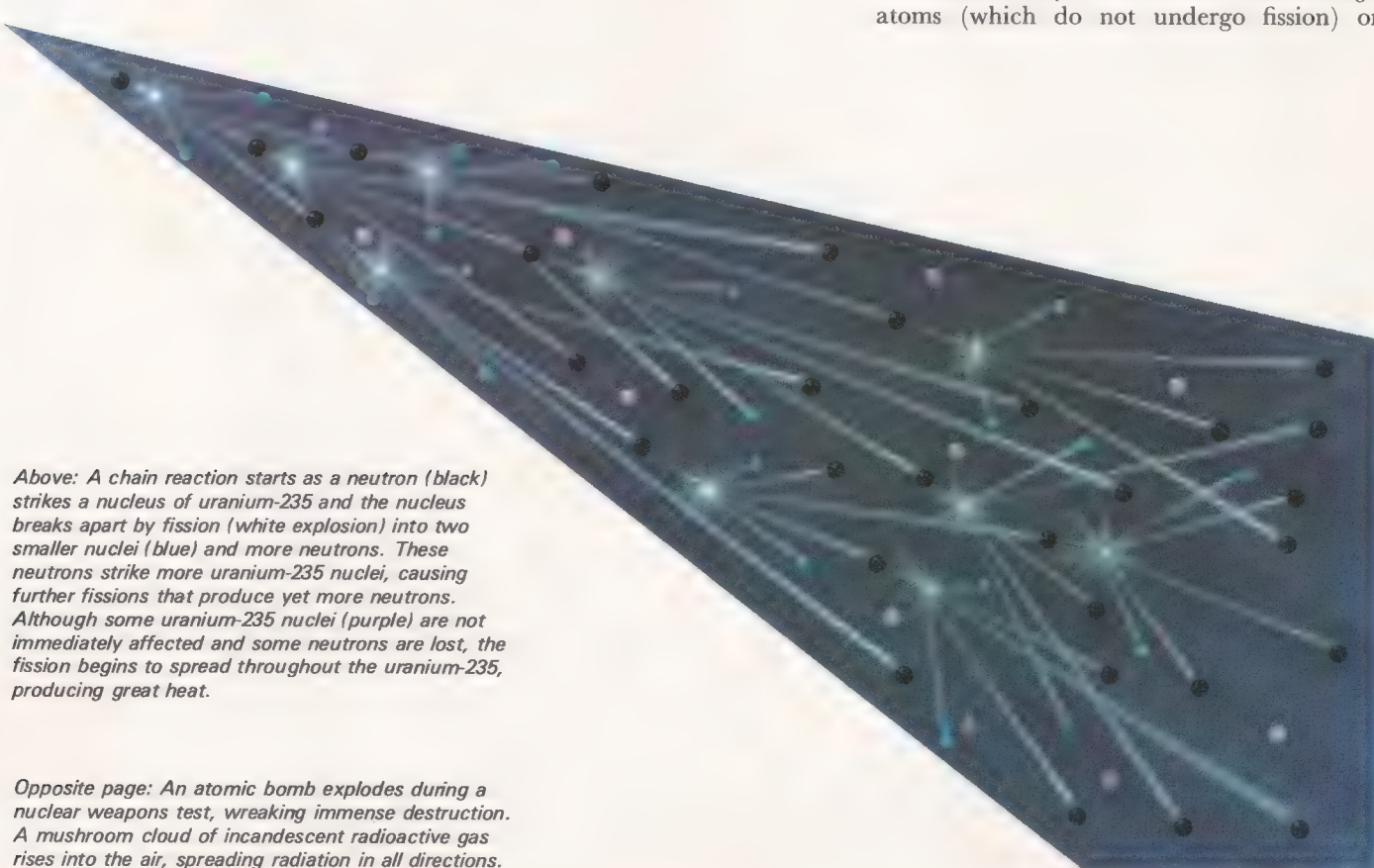
Enrico Fermi, the Italian scientist who was the first to produce nuclear fission and to achieve a chain reaction.

in countries ruled by dictators. Fortunately their actions caused their leading scientists, including Fermi, to flee and follow up the consequences of the discovery elsewhere. Most went to the United States where, prompted by the eminent scientist Albert Einstein (1879–1955) who feared the Nazis were developing nuclear power, the government began a huge research programme to put nuclear fission to use.

The Chain Reaction

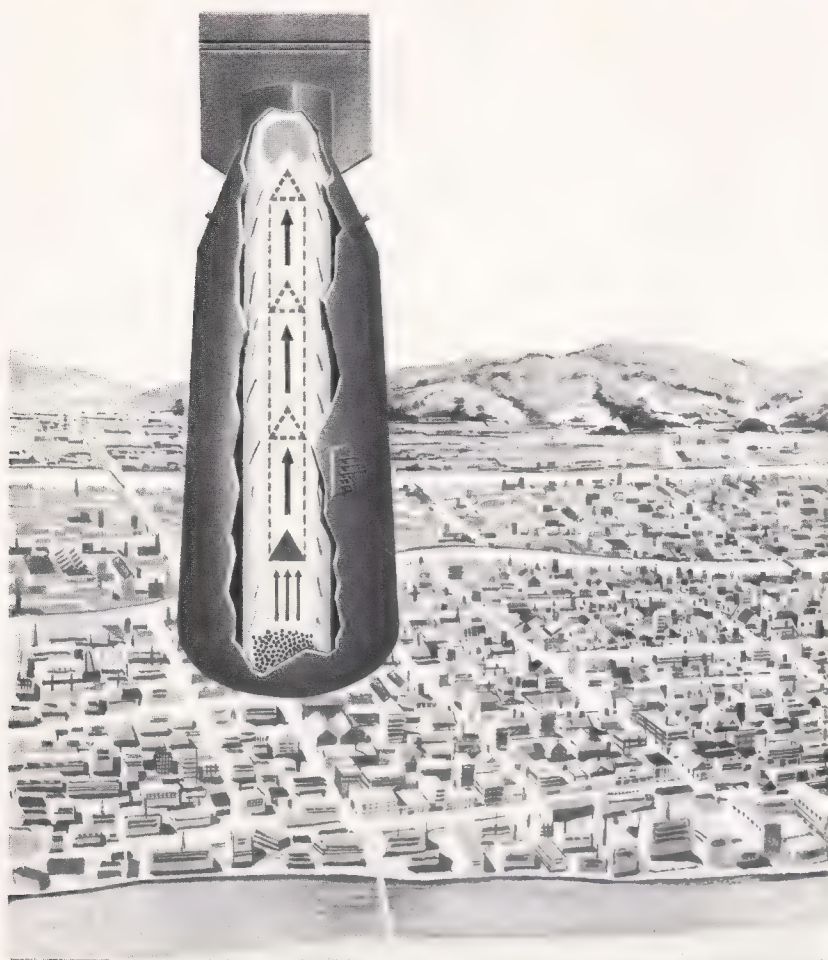
Fermi realized that if the fission of a uranium-235 atom produces more neutrons than it absorbs, then these neutrons may strike other U-235 atoms, which will themselves undergo fission producing yet more neutrons, and so on. A *chain reaction* would occur as fission spread rapidly throughout the atoms in a sample of uranium-235. At each fission, heat is produced and the chain reaction would cause a vast amount of heat to be released. This heat would cause the uranium sample to explode with immense power if the chain reaction proceeded unchecked. But if it could be controlled, the heat could be turned into other kinds of energy, such as electricity. A vast new source of power lay within man's grasp but, as it was wartime, it had to be developed for weapons as well as for beneficial use.

A chain reaction obviously does not occur in natural uranium, otherwise we would not be here. Only one in every 140 uranium atoms is a uranium-235 atom. If a neutron should strike this one, it will fission and produce more neutrons, but these will either be absorbed by the heavier uranium-238 atoms (which do not undergo fission) or



Above: A chain reaction starts as a neutron (black) strikes a nucleus of uranium-235 and the nucleus breaks apart by fission (white explosion) into two smaller nuclei (blue) and more neutrons. These neutrons strike more uranium-235 nuclei, causing further fissions that produce yet more neutrons. Although some uranium-235 nuclei (purple) are not immediately affected and some neutrons are lost, the fission begins to spread throughout the uranium-235, producing great heat.

Opposite page: An atomic bomb explodes during a nuclear weapons test, wreaking immense destruction. A mushroom cloud of incandescent radioactive gas rises into the air, spreading radiation in all directions.



Above: The atom bomb that fell on Hiroshima on August 6, 1945, descending over the city. A charge of high explosive at the base of the bomb drove one piece of uranium-235 into another, producing a critical mass of uranium that exploded with a force of 13 kilotons (13,000 tons of TNT).

Below: The scene soon after the explosion. The whole city has been destroyed, except for a handful of the very strongest buildings. Modern nuclear weapons are a thousand times more powerful than the Hiroshima bomb.



leave the surface of the uranium. The chain reaction cannot get started. Even in pure uranium-235, more neutrons are lost than continue the chain reaction if the sample is too small. The amount necessary to sustain a chain reaction is called the *critical mass*, and it is as little as a few kilograms. A sphere of uranium-235 of this mass, which is about the size of an orange, would explode with enough power to devastate a city. But by making the uranium in such a shape that most of the neutrons produced by fission are lost while only a few keep the chain reaction going, the fissions will not multiply into disaster. Useful amounts of heat are continually produced in this way in a nuclear reactor.

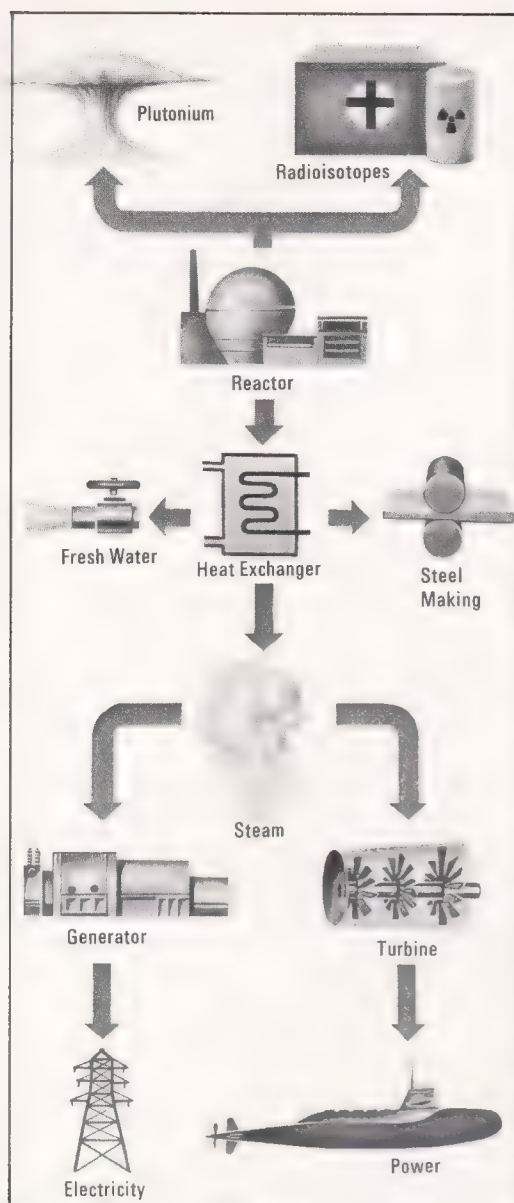
The Dawn of the Atomic Age

Enrico Fermi was the first to succeed in releasing nuclear power, and the first reactor began to work at Chicago in December 1942. The first atomic bomb was tested in the United States in July 1945 and a month later, bombs were dropped on the cities of Hiroshima and Nagasaki in Japan. The cities were flattened in a second and over 100,000 people killed, not only from the force of the explosion and the raging fires that followed, but also from the invisible radiation that shot through the air as the bombs exploded. Thousands were to die later from radiation sickness, and people who were near the explosions are still dying from the effects even today. World War II was brought to an end and the world has lived in an uneasy peace since, as other nations have developed nuclear weapons.

If the masses of all the products of fission, including the neutrons released, are added up and compared with the total mass of the original uranium nucleus and the neutron that caused it to undergo fission, then the scales would tip slightly. The products of fission have a total mass slightly less than that of the uranium nucleus and neutron that produced them. This lost mass is turned into the energy produced by fission and, as Einstein's Special Theory of Relativity shows (see pages 80-1), a little mass is equivalent to a vast amount of energy. This is why nuclear reactions produce such huge amounts of energy; it is always at the cost of a small loss of mass. This loss is almost negligible. If all the atoms of uranium-235 in a piece the size of a golf ball were to fission, the energy produced would be equal to that made by burning about 50 rail trucks full of coal.

Nuclear Fuel

Uranium is a rare metal and as less than one per cent of it is uranium-235, it might seem that fuel for nuclear reactors is hard to obtain. In fact, pure uranium-235 does not have to be used in reactors. Some reactors even work with natural uranium, but most use uranium compounds containing a higher proportion of uranium-235 than is found in nature. To *enrich* the fuel in this way, uranium-235 must be separated from the common



Left: A nuclear reactor is needed to harness nuclear power. By irradiating elements with neutrons, it can produce plutonium or radioisotopes. The heat it gives can be used, via a heat exchanger, to distil fresh water from sea water, to power a blast furnace for steel making, and to raise steam. The steam may then be used to produce electricity, or motive power in a nuclear submarine or ship.

Below: Waste disposal is a serious problem in the nuclear power industry. After leaving the reactor, the waste is stored in huge tanks of water, seen here dwarfing a technician. The water absorbs the initial radioactivity. However, some wastes remain radioactive for many centuries, and disposal methods must be just as long-lived.



How a Reactor Works

The designers of nuclear reactors face many problems. They have to get the heat produced by fission out of the reactor but they have to keep the radiation and neutrons emitted when fission occurs inside the reactor. The chain reaction must proceed at just the right pace—too slow and it will stop, too fast and the reactor will overheat. Another problem concerns the neutrons circulating in the reactor. These must not be allowed to take up too much energy because nuclear fuel undergoes fission most readily when struck by slow neutrons. Fast-moving neutrons tend to bounce off the fissile atoms instead of entering them and producing fission.

The centre of the reactor is called the *core*. Here the nuclear fuel is housed inside rods. Around it is placed a *moderator*—a substance that acts to slow neutrons, such as graphite or water. *Control rods* made of neutron-absorbing materials such as cadmium or boron are also inserted into the core. If the chain reaction needs to be slowed or stopped, the control rods are pushed into the core to remove some of the neutrons causing fission. To remove the heat produced in the fuel rods, a liquid or gaseous coolant is pumped through the core. When it leaves the core, it

isotope, uranium-238. The separation process depends on the slight difference in mass between the isotopes. The method commonly used is gaseous diffusion, in which compounds of both isotopes diffuse through porous membranes. Lighter substances diffuse faster than heavy substances and, by repeated diffusion, the two isotopes are separated. Other enrichment processes include whirling the compounds in a centrifuge to separate the isotopes, and firing laser beams at the isotopes to excite one and not the other. The excited isotope can then be collected on an electric plate. The laser method has still to be developed to full-scale use but it should be less expensive than other methods.

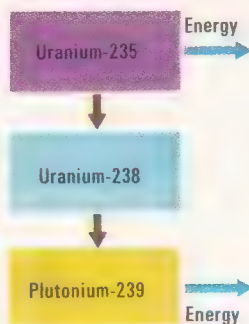
Other fuels exist apart from uranium-235 and natural or enriched uranium. Plutonium-239 is also a fissile material that can be used in nuclear reactors and in weapons—the Nagasaki bomb was a plutonium weapon. It is made by subjecting uranium-238 to bombardment with neutrons in a nuclear reactor. Another fuel, uranium-233, is made in a similar way from the common thorium isotope, thorium-232.

goes to a heat exchanger, where it gives up its heat before returning to the core. The whole core is surrounded by a thick shield of concrete or immersed in a deep tank of water to prevent neutrons and gamma rays escaping. The control rods are operated and new fuel is fed into the reactor by machines outside the core.

There are several different kinds of reactors. The first were the Magnox reactors that power British atomic power stations. They employ natural uranium metal as fuel, graphite as moderator and carbon dioxide as the coolant. In the United States, many reactors use water both as coolant and moderator and enriched uranium oxide as fuel. Canada's reactors employ natural uranium oxide as fuel and heavy water as coolant and moderator. All these reactors work well, and the selection of a particular kind depends mainly on the availability of the various fuels and moderators.

Breeding Fuel

Another kind of nuclear reactor can actually produce more fuel than it consumes. This is the *fast reactor* or *breeder reactor*, which has just begun to produce useful power. It has no moderator and its fuel is highly enriched uranium or plutonium. The core is small and the chain reaction proceeds rapidly, producing greater amounts of heat than with the other 'thermal' reactors. Large amounts of neutrons

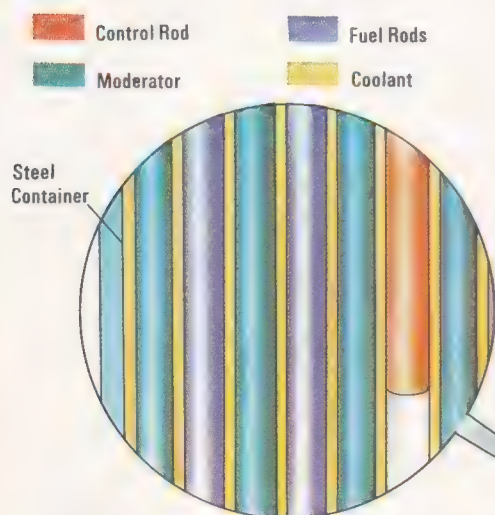


Above: In a fast reactor, fuel highly enriched in uranium-235 produces energy. Large amounts of neutrons are also given out, but a blanket of uranium-238 placed around the reactor core absorbs the neutrons, which convert it into plutonium-239. This plutonium isotope is then separated and later used as fuel in other nuclear reactors. In this way, the fast reactor makes more fuel than it consumes.

are produced but absorbed in a blanket of uranium-238 placed around the core. This does not cause fission in the uranium, but converts it into plutonium-239. This plutonium can later be separated and then used as a fuel for the fast reactor. In this way, the fast reactor produces fuel as it consumes it. By converting non-fissile uranium-238 into a useful fuel, the fast reactor could extend the world's reserves of nuclear fuel by sixty times! However, there are disadvantages. The core operates at such high temperatures that a liquid metal has to be used as coolant, and hot liquid metals are very difficult to handle. Many scientists are not convinced that fast reactors are completely safe; because they are small and the fuel highly enriched, an accident in which the core melted might possibly bring together sufficient fuel to cause a nuclear explosion. This could not happen with a thermal reactor.

Using Nuclear Power

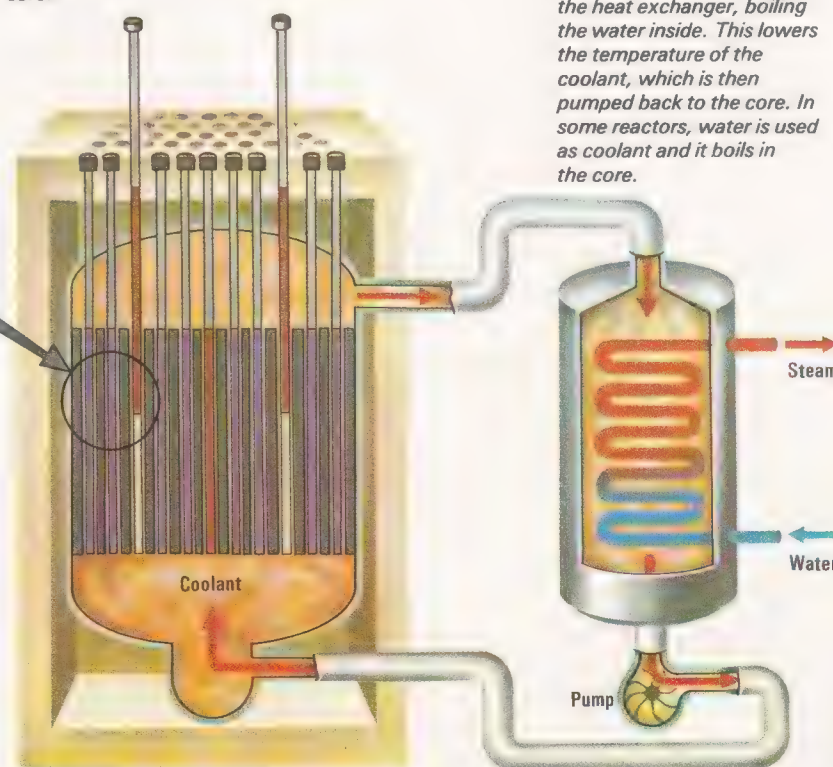
A nuclear reactor produces its useful energy mainly in the form of hot steam, which issues from the heat exchanger connected to the reactor core. The generation of electricity is the main task that we have given to this energy. As in oil-fired and coal-fired power stations, the steam drives turbines which in turn power large generators. The electricity produced is then fed into the grid—the national network of electricity supply lines.



The Core of the reactor is built inside a strong steel container. It contains fuel rods made of fissile materials housed within tubes. The fuel rods produce heat as the fuel undergoes fission. The control rods are moved in and out of the core to vary the flow of neutrons in the core, controlling the rate of fission and therefore the heat produced. The rods are surrounded by a moderator, which slows the neutrons produced by the fuel so that fission proceeds steadily. Through the core flows a coolant, a liquid or a gas, which removes heat from the core.

The Biological Shield is a thick layer of concrete surrounding the core. It prevents harmful radiation escaping.

The Charging Floor lies above the core of the reactor. Here, fuel rods are inserted into the core and removed after use. The control rods are operated from outside the core.



THE NUCLEAR REACTOR

The Heat Exchanger takes heat from the core. Hot coolant from the core flows around the central tube of the heat exchanger, boiling the water inside. This lowers the temperature of the coolant, which is then pumped back to the core. In some reactors, water is used as coolant and it boils in the core.



You cannot know whether you are using electricity generated by a nuclear power station or not, but the difference between the two kinds of power stations is obvious if you should visit them. A conventional power station has tall chimneys pouring smoke into the sky, and there is a noisy clatter as trains bring in fuel and it is transported to the boilers to raise steam. A nuclear power station is clean and silent, for the reactor produces no pollution and will run for long periods without refuelling. The first full-scale atomic power station opened in Britain in 1956. The United States now produces the most nuclear power, though a much higher proportion of electricity is generated by nuclear power stations in Britain and France. By the year 2000, this proportion could be as high as a half in leading industrial nations.

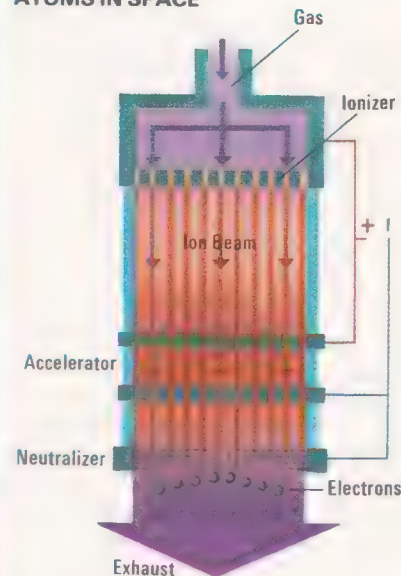
The other main use of nuclear power has been in submarines. Submarines were previously propelled by oil-fired engines, which need air to burn their fuel. Batteries charged by running the engines at the surface powered them underwater. Nuclear submarines are

Above: The core of a reactor under construction. When complete and in use, the tubes will contain fuel rods, control rods, moderator, and coolant to remove heat from the core.

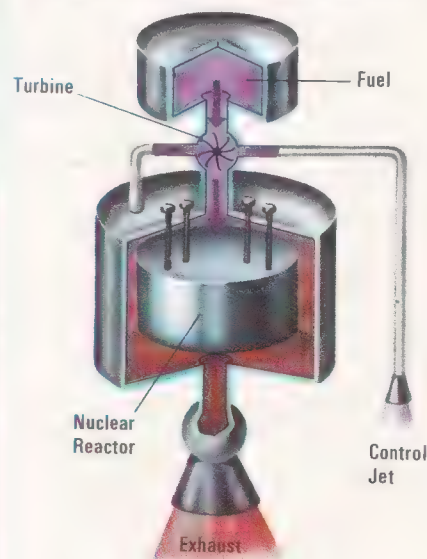
driven by turbines powered by a small reactor, and can stay submerged for months on end. Some nuclear ships have been built, but have not proved economic to run. However, if oil becomes scarce, the nuclear ship may come into its own. Nuclear energy can also be used to make fresh water by distilling sea water.

Other possible uses for nuclear power include using the hot gases from the core to heat blast furnaces, power chemical production, drive gas turbines to produce power more efficiently, and propel spacecraft.

ATOMS IN SPACE



An Ion Engine may be used for space travel in the future. It is powered by electricity, obtained either by solar cells or a nuclear generator, and uses a gas as a propellant. The gas atoms pass through a charged metal screen to ionize them, and are then accelerated in an electric field. As the ion beam leaves the exhaust, its electrical charge is neutralized by adding electrons.



A Nuclear Rocket Engine would simply heat a propellant gas to make it expand and rush from the exhaust. Some of the gas would be diverted to drive a turbine to pump the fuel from its tank and to power control jets.

Cosmic Power

As World War II drew to a close and it had become obvious to scientists that the power of the nucleus could be unlocked, they began to look at other possible nuclear reactions. Maybe others could be found in which mass would be lost and turned into energy. Perhaps even greater amounts of energy could be produced, and from cheaper materials than uranium or plutonium. It soon appeared that hydrogen isotopes (deuterium or hydrogen-2, and tritium or hydrogen-3) would combine to form helium isotopes and release a great deal of energy.

Such energy-producing reactions are called *fusion reactions*, because they build up nuclei rather than break them apart as in fission. Fusion is much more powerful than fission—indeed, it powers the Universe. Fusion of hydrogen to form helium takes place in the Sun and stars, and all life on Earth is supported by the tiny fraction of the immense amount of thermonuclear energy produced by the Sun that reaches us as heat and light.

One atom in every 6000 hydrogen atoms is a deuterium atom and the isotope can easily be obtained by passing an electric current through water; vast amounts of deuterium therefore exist and it is cheap. Tritium is an artificial isotope made from the metal lithium. But there is one great snag to fusion power; the reaction can only be started by heating the isotopes to the vast million-degree temperatures that exist in the Sun. There is only one way of achieving these conditions on Earth—exploding an atomic bomb. Fusion, or thermonuclear fusion as it is also known because it takes place only at high temperatures, was therefore soon achieved, but only in weapons.

The Hydrogen Bomb

The first thermonuclear weapon, or hydrogen bomb as it is often called, was exploded in a test by the United States in 1952. It detonated with a force of 10 megatons—equal to exploding 10 million tons of TNT or conventional high explosive. The power of this terrible weapon was 750 times greater than that of the first atomic bombs, and sufficient to wipe out any capital city. In the hydrogen bomb, an atomic-bomb trigger sets off a fusion reaction in a compound of deuterium and lithium, the lithium instantly producing tritium that reacts with the deuterium. But military scientists also thought of a way of increasing the power of the bomb by encasing it in natural uranium. The powerful neutrons produced by fusion then cause an even greater fission explosion in the uranium casing. In 1961, Russia tested the most power-

ful bomb ever made. It exploded with a force of 57 megatons.

A fission bomb produces a deadly cloud of radioactive fission products. Some of these products rain down on the area around the explosion, causing radiation sickness in anyone caught there—as at Hiroshima and Nagasaki. The remainder of the dust rises into the atmosphere and spreads out before returning to the ground, often in rain. This radioactivity that descends invisibly from the skies is called *fall-out* and it may enter the body. Fusion does not produce radioactive products and so a fusion bomb is 'clean' and devoid of fall-out—apart from radioisotopes produced as the casing vaporizes. But such a weapon is not really clean; it kills by the deadly radiation that it produces and death, as we have seen in Japan, may take a very long time. The uranium jacket around the hydrogen bomb produces immense amounts of fall-out and such bombs have become known as 'dirty' bombs.

Concern at the increase in world-wide radiation levels produced by fall-out from nuclear weapon tests forced many nations to agree to a partial ban on tests in 1963. Weapon tests in future would only take place underground, so that fall-out would not enter the atmosphere. Radiation levels have now declined, although France and China have tested bombs in the atmosphere since then.

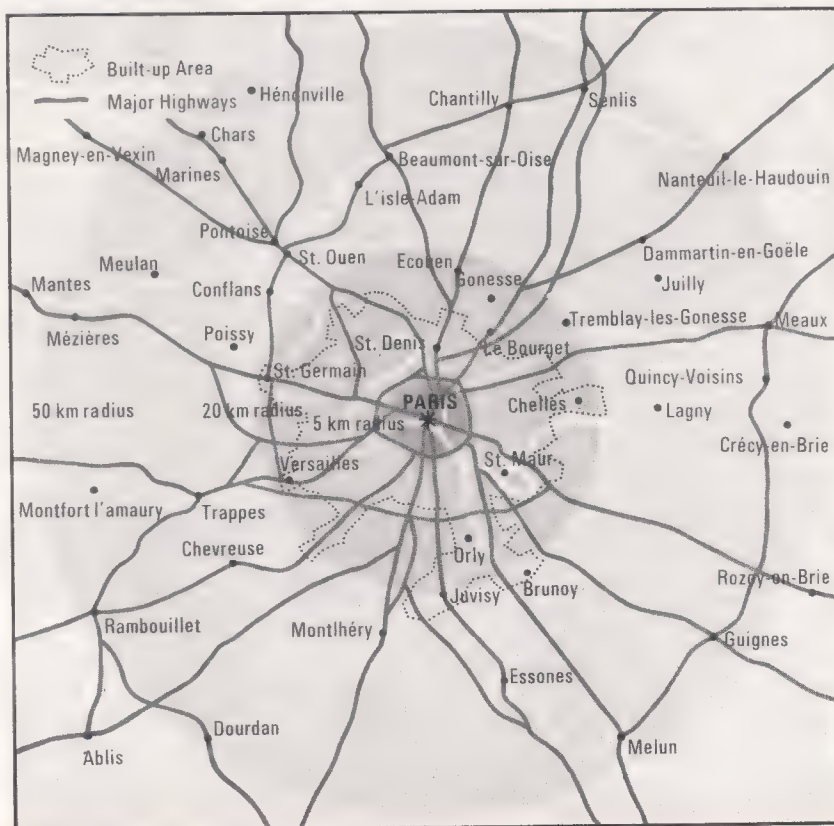
Controlling Fusion

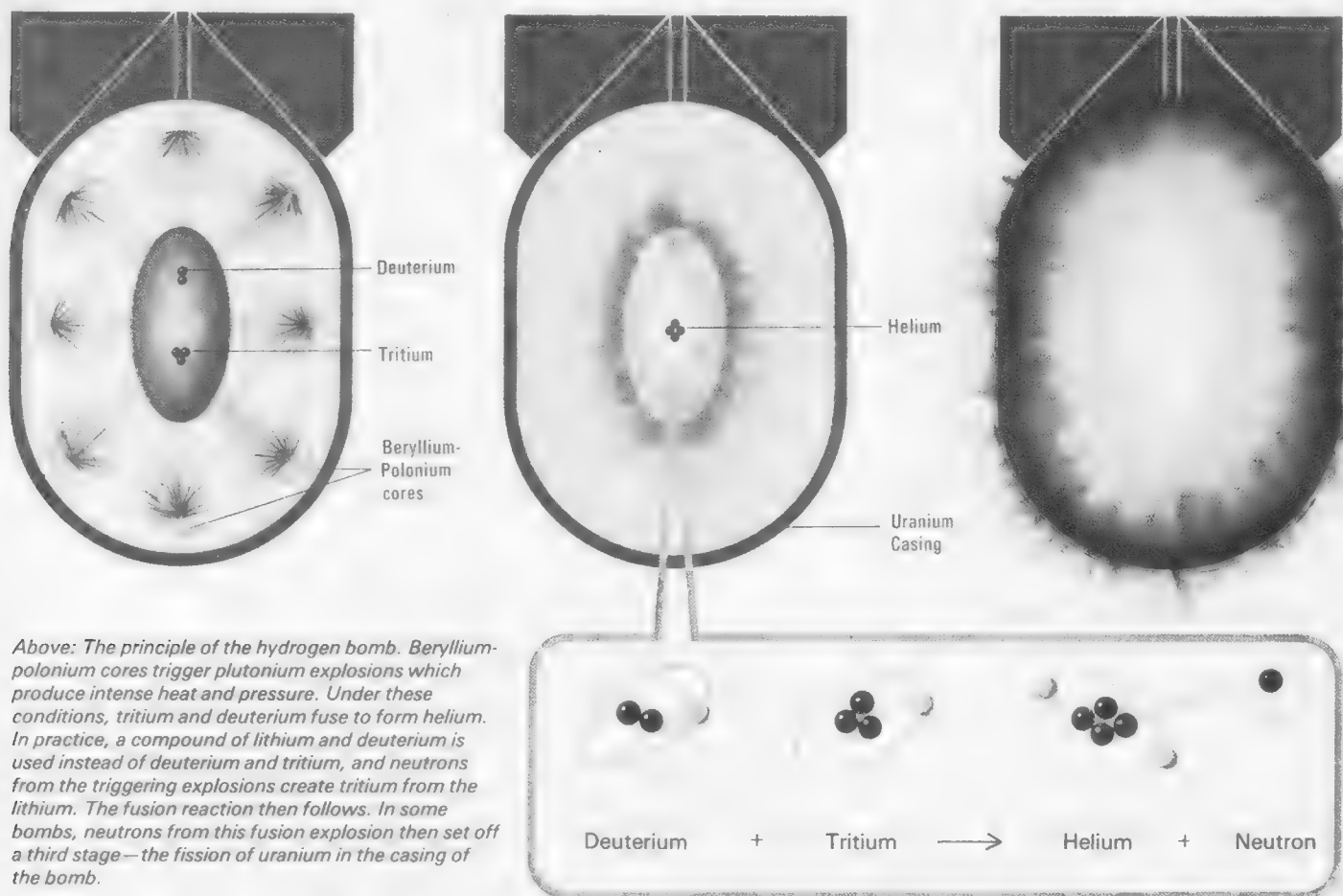
As hydrogen bomb tests began to poison the atmosphere, many scientists began to work to find ways of controlling fusion to produce useful power. The problems were immense,



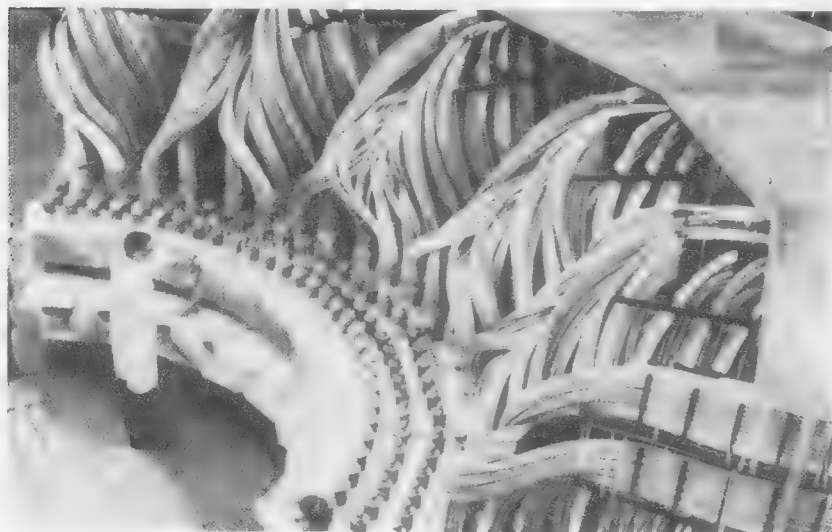
Above: Two nuclei of deuterium, or hydrogen-2, fuse together to give one nucleus of helium-3 and a neutron. The fusion produces large amounts of energy.

Below: If a 10-megaton hydrogen bomb exploded over the centre of Paris, it would totally destroy the city out to a distance of 20 kilometres from its centre. The rest of the city would be in flames, and people would be burned by the heat of the explosion as far as 50 kilometres away. Radiation sickness would cause the deaths of many more.





Above: The principle of the hydrogen bomb. Beryllium-polonium cores trigger plutonium explosions which produce intense heat and pressure. Under these conditions, tritium and deuterium fuse to form helium. In practice, a compound of lithium and deuterium is used instead of deuterium and tritium, and neutrons from the triggering explosions create tritium from the lithium. The fusion reaction then follows. In some bombs, neutrons from this fusion explosion then set off a third stage—the fission of uranium in the casing of the bomb.



Above: Scientists assemble a machine for a fusion experiment. In the circular tube, a beam of deuterium is squeezed and heated by a strong magnetic field. So far, no one has succeeded in harnessing fusion power, but work is going ahead in several countries as fast as possible to find a way of doing so.

far greater than those in making the first fission reactor. The main one was how to heat the hydrogen isotopes to the great temperatures needed to start fusion. How could such a temperature be achieved in a machine without it vaporizing?

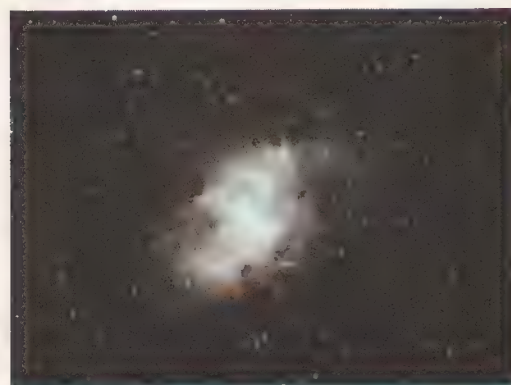
The main line of research has been to confine the isotopes in a magnetic field within a container. A high electric current is passed through the hydrogen to heat it up and form a plasma—a gas composed of charged atoms—while a magnetic field compresses the plasma and keeps it from touching the walls. Even if it does touch the container, vaporization does not occur because very small amounts of hydrogen are heated; the

walls simply cool the plasma more than the plasma heats the walls.

To achieve fusion, more than high temperature is needed. There must be sufficient plasma present so that the nuclei will meet and fuse, and the high temperature must be produced for long enough for this to happen. The right combination of all these factors has so far proved impossible to achieve. The plasma does not remain stable and twists out of the magnetic field before sufficiently high temperatures or densities can be attained. Research is going on in many countries to improve the containment of plasma, but success still appears to be distant. Even if controlled fusion is achieved, it is now by no means certain that it will produce more energy than is put into the fusion reactor to heat and contain the plasma.

Fusion scientists are therefore looking at other ways of obtaining controlled thermonuclear power, and a new method looks promising. By firing laser beams or electron beams at pellets of solid deuterium and possibly tritium, fusion might occur in the pellets. The beams would heat the pellets to very high temperatures, but the heating would be so rapid that the interior of the pellets would be placed under great pressure before they flew apart. In these conditions, fusion might occur. The pellets would be very small and the resulting explosions would not be sufficient to wreck the reactor, but enough to produce heat in immense quantities. The heat could then be converted to electricity.

Anatomy of the Universe



Above: The Great Nebula in Orion (top) is an emission nebula. Radiation from the hot stars in the nebula makes the gases in the nebula emit light. The Horsehead Nebula (centre) is a dark nebula; it is not illuminated and stands out against the background of stars. The Crab Nebula (bottom) is the remains of a supernova that exploded in 1054.

Right: The Pleiades or Seven Sisters are a group of stars that can be easily seen in the northern sky. The stars are surrounded by dust clouds that reflect light from the stars, producing a misty appearance.

So far, in our investigation into the nature of matter, we have looked inward to find the basic particles from which everything in the Universe is assembled. Now let us look outward into the Universe to see what kinds of strange and wonderful bodies exist there. The sizes and distances involved are as great as those in the atom are small—and just as difficult to imagine. But we can use the same kind of analogy as we did with the atom. The illustration on page 12 shows us that if an atom were enlarged to the size of the nail on your little finger, then your hand would be big enough to grasp the Earth. Continuing this analogy, if all the atoms in the Earth each swelled to the size of the Earth, then the Earth would be the size of the Universe! That is, the Universe is so great that our world is as tiny and insignificant in the vastness of the Universe as is a single atom in the whole of the Earth.

Even though they are composed of the same atoms as we have on Earth, the kinds of bodies that are to be found throughout the vast reaches of the Universe are very different to the things that atoms make up on Earth. In the centres of stars, atoms may be so highly compressed that a matchbox full of material would weigh a million tons. In between the stars, there are atoms too, for space is not totally empty. However, every cubic centimetre contains on average only one atom or molecule, and space is a much rarer vacuum than we can ever achieve on Earth. Temperatures vary greatly too, from the intense cold of space—almost as cold as it is



The stars form groups in the sky known as constellations. The stars in a constellation are not in fact near each other but only appear to be when seen from Earth. The constellations reminded ancient peoples of familiar shapes and they were named accordingly, such as Taurus (The Bull, above) and Scorpio (The Scorpion, below).

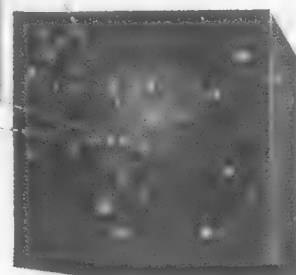
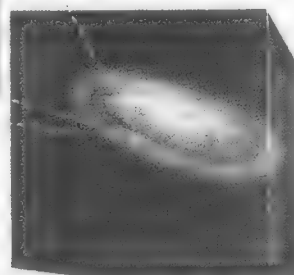
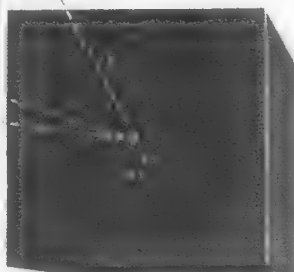
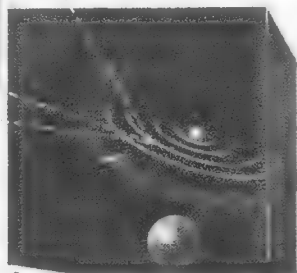
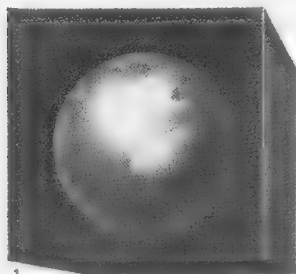




Above: Stars go through different stages in their lives. All are born in a cloud of interstellar gas and dust (1). The cloud condenses (2) into a warm red star that commences to heat up. Many become stars like the Sun (3), and after comparatively short lives swell into red giants (4). The giant star expels its outer layers (5) and shrinks to a cool white dwarf (6). Larger stars become blue giants (7), which are very hot, and then swell into red supergiants (8). The supergiant then collapses under its own gravitation (9) and explodes in a supernova (10). From this, a tiny but extremely dense neutron star (11), may form, or possibly a black hole (12), which has extreme gravitation. Stars smaller than the Sun evolve into small red stars (13) that do not grow very large and end their lives as cold black dwarfs.

possible to be—to temperatures of millions of degrees at the centres of stars. Away from our comfortable home planet, the Universe is a place where extreme conditions are to be found.

Scattered throughout space are thin clouds of gas and dust. The gas consists of molecules of hydrogen and simple compounds such as water and ammonia. Radicals, which are incomplete molecules with atoms missing, are also present. The dust consists of tiny specks of matter such as graphite and sand. These clouds are called *nebulae*, and they may be either bright or dark. Bright nebulae are a spectacular sight through a telescope, looking like vivid coloured clouds hanging in space. They are mostly too faint to be seen with the naked eye, although the Great Nebula in Orion can be seen as a dim, misty patch beneath Orion's belt (that is, to the south of it). Bright nebulae shine because they are illuminated by the light of stars scattered throughout the cloud. Dark nebulae appear as black clouds in space, standing out against the light of stars behind them.



ASTRONOMICAL DISTANCES

The distances between stars and galaxies are so vast that astronomers measure them in *light years*. One light year is the distance that light travels in a year, and it is equal to 9.460 million million kilometres. Another unit used in astronomy is the *parsec*, which is equal to 3.26 light years. The *astronomical unit* is sometimes used for measuring distances in the solar system. It is equal to the distance from the Earth to the Sun—almost 150 million kilometres.

QUASARS AND PULSARS

Astronomy was shaken by the discovery in the 1960s of two entirely unsuspected kinds of bodies—*quasars* and *pulsars*. Quasars have massive red shifts—indicating that they are moving very rapidly and are therefore to be found at the edges of the Universe—but they are unbelievably bright for such distant objects. No-one can explain how anything can be so bright, and quasars remain the great mystery of the Universe. Perhaps they are not so distant, which would explain why they appear bright but not why they have large red shifts. Possibly they could be bodies ejected from our Galaxy and moving away from it at incredible speeds.

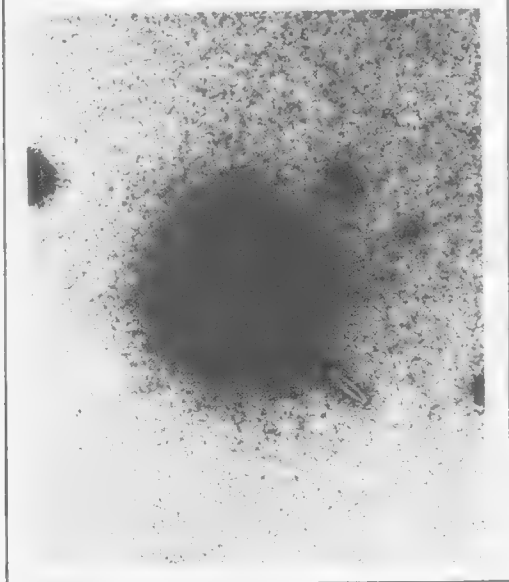
Pulsars produce pulses of light and radio waves as regularly as the ticking of a very accurate clock. At first, astronomers wondered if the pulses were signals from a far-off civilization, but they are meaningless. Pulsars are thought to be neutron stars—stars that have undergone such a massive collapse that their atoms have become so compressed that electrons are forced into the protons in the nuclei, forming neutrons. Such stars would be balls of neutrons and extremely dense—a matchbox full of their material would weigh a million tons! The immense compression would reduce the star's diameter to about 20 kilometres and as it collapses it would increase its speed of rotation by the principle of conservation of momentum (see pages 78–9). The pulsar would produce beams of energy that would sweep round as it spins, rather as the lamp in a lighthouse does, making it appear to flash on and off many times a second. The formation of a neutron star would require immense energy, and pulsars have been found where supernovae have exploded.

Above: To get an idea of the size of the Universe, imagine first a cube of space big enough to enclose the Earth (1). A cube 40,000 times larger would enclose the Sun and all the planets out to Jupiter (2). A cube 40,000 times bigger again is large enough to include the Sun and the nearest star (3). Another cube 40,000 times larger still is big enough to enclose the Galaxy (4). Finally the sides of a cube yet another 40,000 times larger would be equal to a third of the diameter of the known Universe.

The Birth and Death of Stars

Nebulae are of special interest to astronomers. Not only are they the most beautiful bodies to be viewed in the heavens, but they are also the birthplaces of stars. In a cloud of gas and dust, the molecules and specks of matter attract each other by gravity. Parts of the cloud begin to condense as the particles move towards each other. Their motion transforms into heat, and the cloud gets hotter as it condenses. Eventually, over millions of years, it gets dense and hot enough for thermonuclear reactions to begin, and the mass of matter starts to glow. A star is born.

Stars of many kinds exist in the heavens. Some are giant stars, so large that were one of them suddenly to replace the Sun, then the Earth would be swallowed up in it. Others are dwarf stars, smaller than the Earth. Their colours vary too, depending on their temperature. Blue and white stars are hot, but red stars comparatively cool. The Sun is an unremarkable star, average both in size and colour. Some of these different kinds of stars are basically different from each other, but some are similar stars at different stages in their lives. Many stars burn steadily for thousands of millions of years, using up their hydrogen and turning it into helium to produce energy. The Sun is about 5000 million years old, and will go on burning hydrogen for about the same length of time. Then it will begin to change, as the helium formed fuses into heavier elements. Com-



Left: A negative photograph of the famous quasar 3C 273. This quasar looks like a blue star with a faint jet protruding from it (ringed in white). This quasar was discovered in 1963, and it was the first one in which a massive red shift was detected. It is thought to be 2000 million light years away and if so, it has a diameter of about 10 light years, one ten-thousandth of the average size of a galaxy. Yet it is 200 times brighter than a typical galaxy at such a distance. No one has yet explained how quasars appear to be so bright and so distant.

paratively rapidly, it will swell into a red giant—consuming the Earth as it does so—and then collapse into a dense white dwarf, its life over.

However, some stars end their lives even more catastrophically and suddenly explode. To us, they appear to flare up in brightness for a short time—as if a new star were born in the heavens. Such an exploding star is called a *nova*, from the Latin word for new, although it is of course not new but in its death throes. If the explosion is so vast that the star becomes visible in daylight, then it is known as a *supernova*. Such catastrophes are not frequent, and the last supernova was observed in 1604. The exploding star throws out a shell of material composed of heavier elements formed in the great burst of heating that takes place as the explosion approaches. This material spreads out through space, returning to the dust clouds in which new stars and planets form. In this way, there is a constant recycling of atoms throughout the Universe.

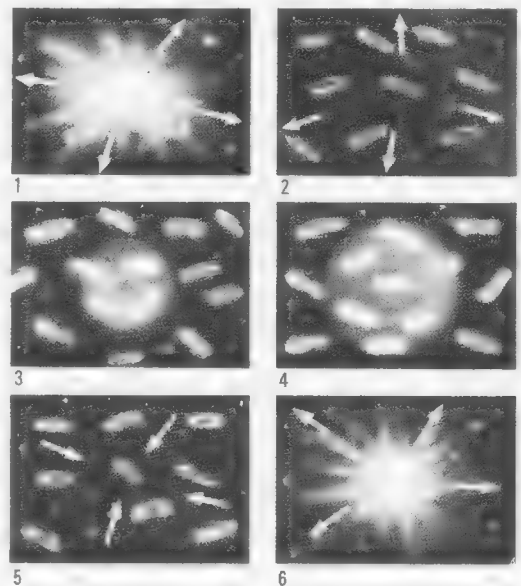
A condensing cloud of gas and dust may give birth to many stars, and most will probably have planets formed as remnants of the cloud condense nearby. Stars are therefore often found in groups—a few in clusters and many as pairs. The Sun is rather unusual in being a lone star, but it is grouped with 250,000 million others in a vast collection of stars known as the *Galaxy*. The Galaxy has a central cluster of stars surrounded by long spiral arms of stars. It is so large that it takes light 100,000 years to cross the Galaxy. The Sun lies along one of these arms, and when we look at the great band of stars known as the *Milky Way*, we are in fact looking into the Galaxy.

The Origin of the Universe

Our Galaxy is only one of many thousands of millions of galaxies scattered throughout space, as far away as we can detect. Nearly all of these galaxies seem to be moving away from us, which would indicate that the Universe is expanding. The farther away a galaxy, the faster it is receding from us. We can measure its speed by detecting the colour of its light; the faster a galaxy moves, the redder its light appears. This effect is known as the *red shift* and by measuring the amount of red shift in the light that comes to us from a galaxy, we can estimate its distance. The most distant bodies are so far away that their light began to travel towards us before the Earth was formed!

If the Universe is expanding, then it must in the past have been smaller than it is today. About 10,000 million years ago, it would have been squeezed into a very small space. This high concentration of matter could have exploded, producing clouds of matter moving away from the explosion and condensing into galaxies of stars as it moved. This theory of the formation of the Universe is called the 'big-bang' theory, and it explains the expan-

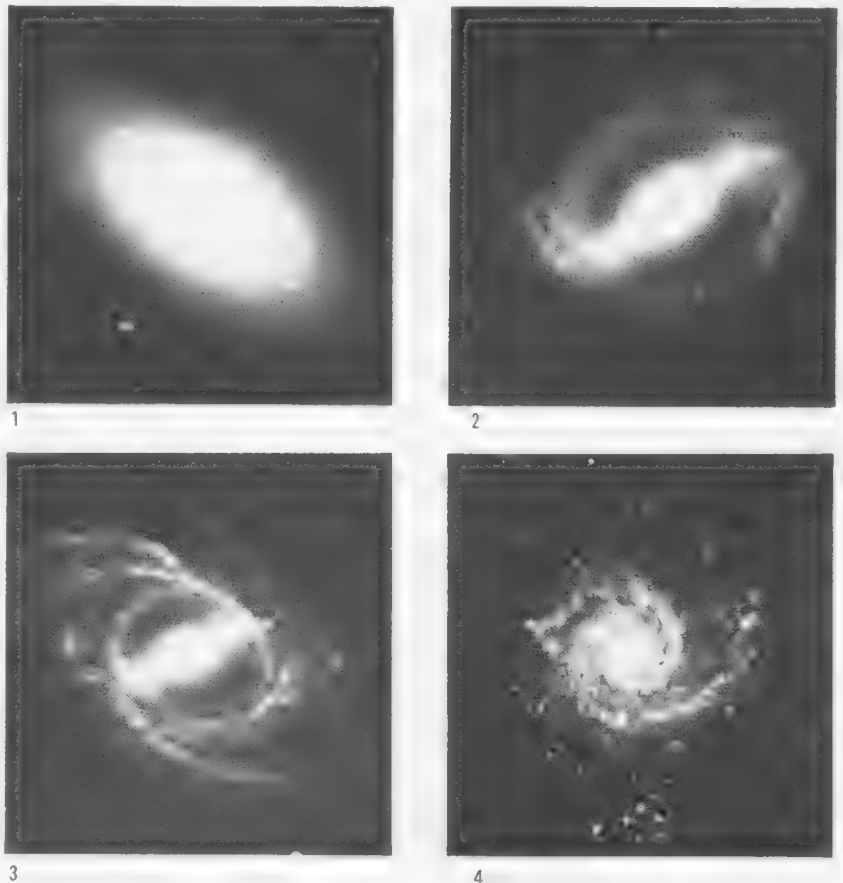
Right: The big bang theory of the origin of the Universe suggests that all matter was concentrated into a very small space about 10,000 million years ago. This matter exploded (1) and the galaxies formed as it spread outwards (2). The galaxies are still moving away from each other, causing the Universe to expand. The steady state theory holds that the Universe continually expands and that new galaxies form in the spaces created by expansion (3 and 4). The oscillation theory proposes that the expansion will one day stop. Then the Universe will contract as all the galaxies come together (5) until a high concentration of matter is formed that will explode (6), producing expansion again. This cycle of expansion and contraction could continue for ever. The evidence at present favours the big bang theory, but this could simply be the expansion phase of the oscillation theory.



sion that we now observe. It also explains the presence of a certain radiation that radio telescopes can detect in the heavens; this radiation would be energy left over from the explosion.

Will the Universe continue to expand for ever and the galaxies disperse into an infinite expanse of space? No one knows, but it is possible that the expansion will slow to a stop and that the Universe will begin to contract under the influence of gravitational attraction. The galaxies will then eventually meet, and another 'big bang' will take place, followed by another expansion, then a contraction and so on, in an endless cycle of oscillations. Perhaps this has been going on for ever and will continue to do so, so that the Universe has no beginning and will have no end.

Below: Three kinds of galaxies: a lenticular (lens-shaped) galaxy without spiral arms (1); barred spiral galaxies with a bar-shaped centre and spiral arms (2 and 3); and a spiral galaxy with a central cluster of stars and open spiral arms (4).





The Family of the Sun

If we had a spacecraft that could move at the speed of light, we could travel about the solar system much as we drive about a city in a car. The Sun would be a mere eight minutes away and all but the three outer planets less than an hour distant. The Moon really would be on the doorstep—just over a second away. Of course, we do not possess such a craft but the spacecraft that man has developed have enlarged our knowledge of the solar system to an amazing extent. Countless theories have collapsed and imaginative ideas been discarded as spacecraft have flown to the Moon and planets, opening their electronic eyes and ears on our behalf.

The solar system is dominated by the Sun, which holds a great family of planets and their attendant moons, asteroids, comets and meteoroids within its iron grip of gravity. All move around it, their motion balancing the Sun's gravity so that they maintain orbits that consign them to a particular part of the

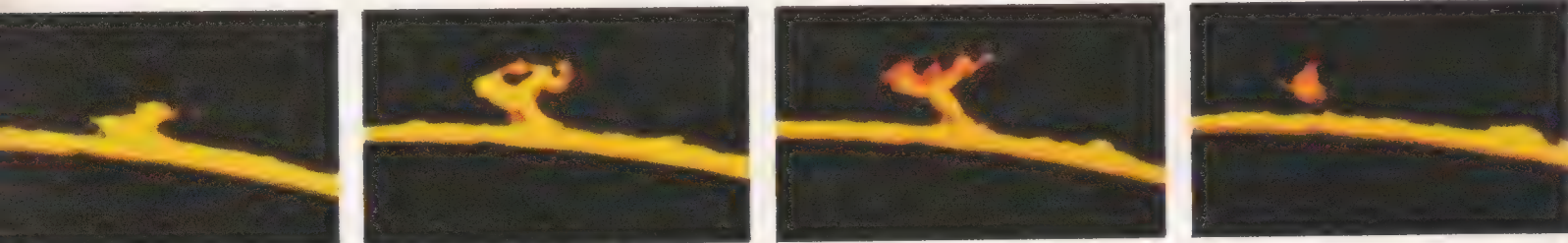
solar system. Every body moves in the same direction around the Sun, because as the Sun condensed from a cloud of gas and dust, the outer edges of the cloud flattened into a spinning disc within which each body condensed. The larger bodies became planets; smaller ones became asteroids and moons orbiting the planets; light masses became comets and the debris left over became meteoroids. The larger bodies heated up as they condensed, gaining molten interiors and throwing out gases that became atmospheres. The largest planets collected atmospheres of hydrogen and helium gas from the cloud.

At the centre of the cloud, where the great mass of hydrogen concentrated, the Sun began to shine by thermonuclear fusion. If Jupiter had been bigger, it would also have gathered enough hydrogen to start burning and the solar system would have had two suns, perhaps with planets performing complicated orbits around them both. The Sun's energy is



Above: Sun spots on the surface of the Sun. They look like dark holes but are in fact regions of cooler gas shining less brightly than the hotter surrounding gas.

Below: A solar prominence, a vast tongue of flame, shoots from the Sun's surface. This sequence of photographs was taken in a few minutes.





Above: The planets of the solar system with their moons. From left to right, they are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto. The sizes of the Sun and planets are to scale, and the moons are shown at the angles at which they revolve around their planets. The inset shows the orbits of the planets to scale.



Left: The planet Saturn photographed through a telescope. The planet's shadow can be seen falling across the rings.

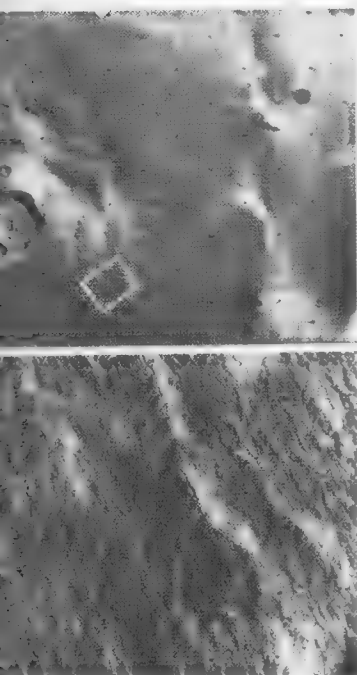
Below: The brilliant Ikeya-Seki comet of 1965 photographed just before sunrise. It is named after the Japanese amateur astronomers who discovered it.

manufactured by fusion in its core, producing a central temperature of about 20 million degrees K. This heat radiates through the Sun's interior, and is also carried to the surface by movements in the interior. The surface seethes as hot gas wells up from below and great tongues of flame burst thousands of kilometres out into space. Dark areas known as *sunspots* form and disappear as magnetic disturbances occur and flares may break out. Violent showers of particles fly out from the Sun, streaming through the solar system.

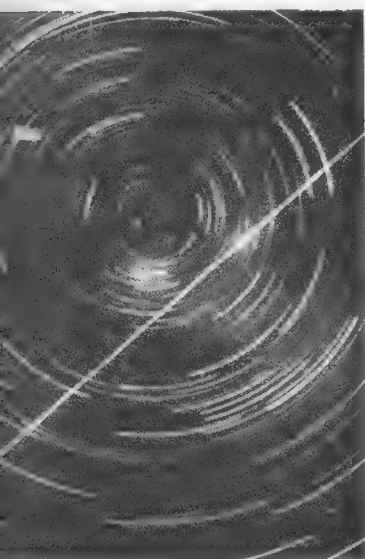
The main recipients of the Sun's vast outpouring of energy are its planets. There are nine that we know of, including the Earth. The smallest, Mercury, is also the nearest and it is locked by the Sun's gravity in a rotation rate that is exactly two-thirds of its period of revolution. This means that a day on Mercury, from one sunrise to the next, lasts for two of Mercury's years! The surface of the planet is rocky and covered with craters like those on the Moon. Impacts by smaller bodies falling from space and

eruptions by volcanoes formed the craters and, in the lack of an atmosphere, they have never worn away. Venus, on the other hand, has a thick atmosphere laden with acid and it is extremely hot. Pictures from the surface sent back by a Russian space probe in 1975 show a rugged terrain—a surprise, for such an atmosphere would be expected to erode the terrain rapidly. On Earth, most ancient craters have disappeared with erosion. With its oceans and life-giving atmosphere, Earth is unique among the planets of the solar system. Mars has a thin atmosphere and its surface is cratered, though not so ruggedly as Mercury or the Moon. Its two tiny moons are probably the remains of a shattered larger satellite. Jupiter is the largest planet, composed mostly of liquid hydrogen surrounding a small core of rock. Its atmosphere is divided into bands among which a huge oval known as the Great Red Spot stands out; it is probably a vast storm in the atmosphere. Saturn has claim to be the most beautiful planet with its rings, which are composed of small ice and





Top: A view of Nix Olympica, a volcano on Mars, taken by the space probe Mariner 9. Above: An enlargement of the rectangle outlined in the top picture. It shows lava flows on the slopes of the volcano. The enlarged area measures 48 by 58km.



Above: A meteor streaked across the night sky as this photograph was being made of the stars. The stars appear as curved lines because the Earth rotated during the long exposure, showing how the stars seem to move around the celestial pole, which is at the Pole Star in the northern hemisphere.

dust particles. Saturn is otherwise like Jupiter in its composition. The rings may have formed at the same time as Saturn from debris in the original cloud, or moon-like bodies may have broken into fragments on approaching too near to Saturn. Uranus and Neptune are similar in composition to Jupiter and Saturn, though smaller in size. The outermost planet, Pluto, is small and most probably a moon of Neptune that has escaped its parent planet. Its orbit is very eccentric and in 1987 it will come closer to the Sun than Neptune. The movements of the outer planets suggest that there is an unknown planet way beyond Pluto, but it will prove difficult to locate.

The asteroids are a group of small bodies, many only a few kilometres across, that orbit mainly between Mars and Jupiter. It is thought that they may be bodies that never gathered together to form a planet because of the disturbing influence of Jupiter.

The comets are collections of frozen gas and dust. Being light, they are easily perturbed and their orbits follow unusual paths that thread through the orbits of the planets. As they approach the Sun, the wind of particles from the Sun—the *solar wind*—blows out a glowing tail that stretches back through space behind the head of the comet.

Meteoroids are bodies that vary in size from tiny specks of matter up to large boulders. The Earth sweeps up many meteoroids as it travels through space. Most are so small that they burn up as they rain down through the atmosphere. These are called *meteors* or *shooting stars*. The heavier meteorites survive their fiery passage and crash to the ground. They may cause destruction, but meteorites are the remains of the original cloud that formed the solar system and their age tells us when it formed—some 4600 million years ago.

THE PLANETS

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mean distance from Sun (millions of km)	57.9	108.2	149.6	227.9	778.3	1427	2869.6	4496.6	5900
Period of revolution	88 days	224.7 days	365.26 days	687 days	11.86 years	29.46 years	84.01 years	164.8 years	247.7 years
Rotation period	59 days	243 days retro.	23hr 56min	24hr 37min	9hr 50min	10hr 14min	11hr retro.	16hr	6 days 9hr
Equatorial diameter (km)	4880	12,104	12,756	6787	142,800	120,000	51,800	49,500	6000?
Mass (Earth = 1)	0.055	0.815	1	0.108	317.9	95.2	14.6	17.2	0.1?
Volume (Earth = 1)	0.06	0.88	1	0.15	1316	755	67	57	0.1?
Density (Water = 1)	5.4	5.2	5.5	3.9	1.3	0.7	1.2	1.7	?
Mean temperature of visible surface (°C)	350 (day) -170 (night)	480 (actual surface)	22	-23	-150	-180	-210	-220	-230?
Surface gravity (Earth = 1)	0.37	0.88	1	0.38	2.64	1.15	1.17	1.18	?
Known moons	0	0	1	2	13	10	5	2	0

Below: The American space probe Pioneer 10, which made the first visit to Jupiter. It flew past the giant planet in 1973. The radiation detector found that Jupiter has belts of strong radiation.

Electricity Generator (Nuclear-Powered)

Sun Sensor

Meteoroid Detector Panels

Cosmic Ray Telescope

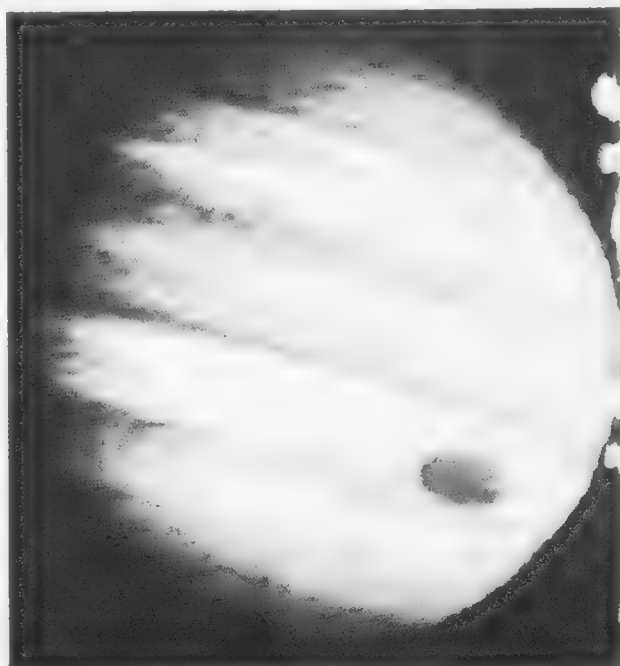
Ultraviolet Photometer

Radiation Detector

Infra-red Radiometer

Magnetometer

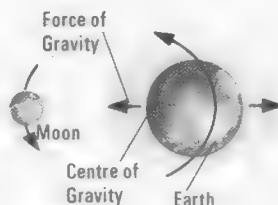
Below: A close-up photograph of Jupiter taken by Pioneer 10. It clearly shows the Great Red Spot, which astronomers now believe to be a violent storm in Jupiter's atmosphere. Pioneer also indicated that Jupiter's surface is probably made of liquid hydrogen.



Universal Forces

Protons and neutrons are held together to make up the nucleus, the nucleus attracts electrons to form an atom, atoms group themselves into molecules, assemblies of molecules make up whole worlds, worlds circle in packs around stars, stars form together in millions to produce galaxies, and the galaxies in turn make up the final supergroup—the Universe. What makes these particles or bodies gather together to form a succession of groups? What holds the Universe together?

The answer is force. Four kinds of forces are necessary to explain the nature of matter from the tiniest part of the nucleus up to the structure of the Universe itself. The strongest force is that holding the nucleus together, and it is called the *strong interaction* because it is a strong force produced by the interaction of mesons in the nucleus. The strong interaction is 100 times stronger than the *electromagnetic interaction*, which is the force between electrically charged bodies (between the electron and the nucleus, or between atoms, or between molecules) or between two magnetized bodies. The third force holds together the particles in the nucleus that break apart when freed from the nucleus, producing radioactivity. It is therefore not very strong and is in fact known as the *weak interaction*, being a million million times weaker than the strong interaction. The final force is the force of *gravity* that pulls us to the ground, keeps the Moon orbiting the Earth and the Earth moving around the Sun, and holds together the solar system and the Galaxy. Because it acts to control the movements of such massive bodies, gravity might seem to be a very strong force. In fact, it is a



Above: Tides rise in the oceans because the Moon's gravity pulls up the water beneath the Moon. The Moon and Earth rotate around their centre of gravity, which is located inside the Earth. This rotation raises another tide on the side of the Earth opposite the Moon.



Above: The Sun's gravity affects the tides. When the Sun and Moon are in line, they act together to raise the big tides known as spring tides.

Below: When the Sun and Moon are at right angles, the Sun lessens the Moon's pull and the small tides or neap tides result.

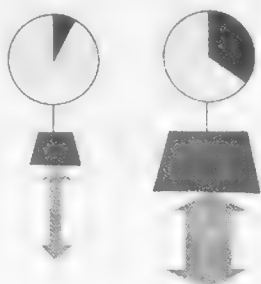
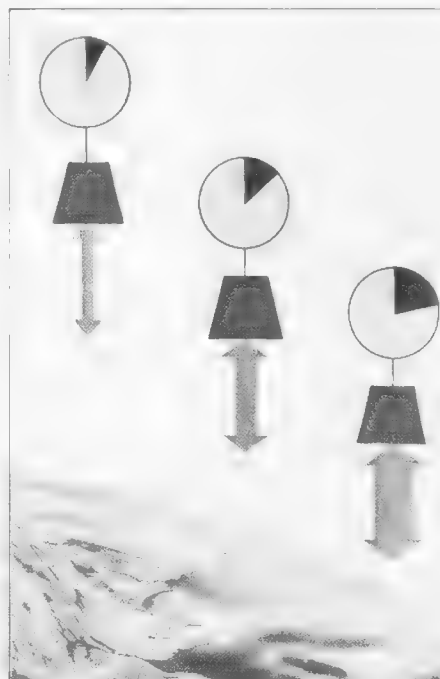


The American scientist Joseph Weber claims to have detected gravity waves coming from the centre of the Galaxy with this apparatus.

very, very weak one and equal to only 10^{-40} or $1/10,000,000,000,000,000,000,000,000,000,000,000,000,000$ of the strong interaction!

The relative strength of these universal forces can, apart from the weak interaction, easily be demonstrated. Two pieces of metal small enough to be held in the hand exert no apparent gravitational force—it exists but is so weak that one does not apparently attract the other. However, if the pieces are magnetized, they will cling together. The electromagnetic force involved is obviously weaker than the strong interaction holding the magnets' nuclei together, otherwise the magnetic force would pull the nuclei apart and the magnets would disintegrate.

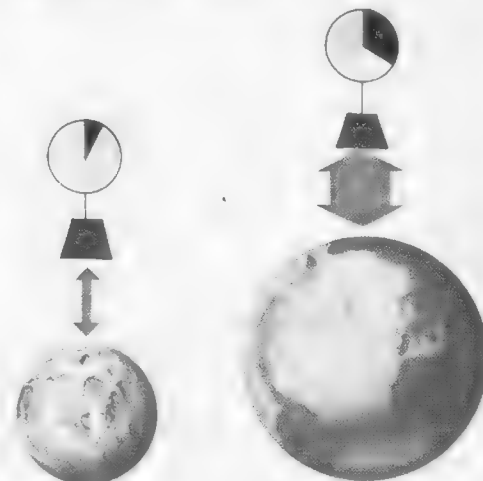
Physicists are searching for a unified field theory—an underlying explanation of the four universal forces so that they may be seen as four varieties of one basic force. If such a theory can be proved, we may have gained an understanding of how the Universe really works.



Above: A larger force of gravity exists between the Earth and a heavy object (right) than a light one (left). The heavy object therefore weighs more.

Left: Gravity varies with distance, so that an object weighs less the farther it is taken from the Earth.

Below: The force of gravity that the Moon exerts on any object is less than that exerted by the Earth, which has a greater mass than the Moon. Any object therefore weighs less on the Moon than on Earth.



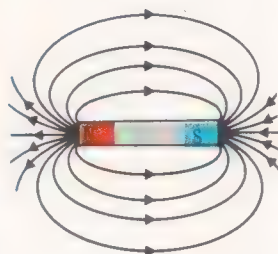


Left: A piece of lodestone, a magnetic iron ore, picks up a chain of pins.

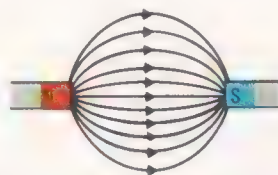
Gravity

Only nuclear particles possess strong and weak interactions, and only electrically-charged and magnetized bodies experience electromagnetic force. But everything yields to the force of gravity, even over the most immense distances. If two bodies of any size are placed in space and shielded from any disturbing influence, they will exert a force of gravity on each other, gradually pull themselves towards each other and eventually meet. This is how stars are born, as dust particles and gas molecules gradually come together in space, drawn irresistibly by gravitation.

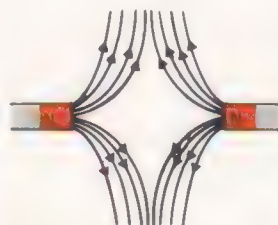
The force of gravity that exists between any two bodies is proportional to their mass and inversely proportional to the square of the distance between them. That is, if one of the bodies doubles its mass, the force of gravity between them will double. But if the distance between their centres should double, then gravity will fall to a quarter ($1/2^2$) of its



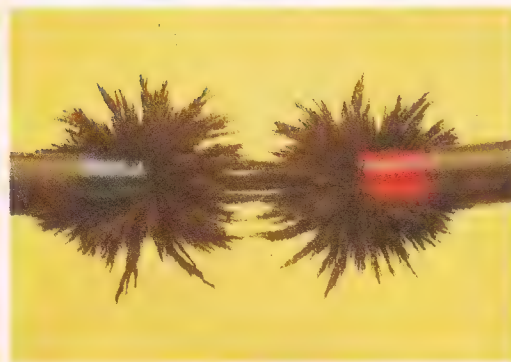
Above: The magnetic field lines that exist around the poles of a bar magnet.



Above: The field lines run from the north pole of one magnet to the south pole of another.



Above: The field lines due to two like poles bend to avoid each other.



Left: By shaking iron filings over a magnet, the magnetic field can be seen as the filings align themselves along the field lines. The pictures show the field around a bar magnet (top) and between two separate magnets (bottom).

previous value; at three times the distance, to a ninth ($1/3^2$); at four times the distance to a sixteenth ($1/4^2$); and so on.

A force of gravity exists between every object on the Earth's surface and the Earth itself. This force acts to pull the object to the surface of the Earth, and is equal to the weight of the object (see page 74). If we double the mass of anything, we double the force of gravity acting on it and therefore double its weight. If we take it away from the surface, gravity will decrease as it gets farther from the centre of the Earth and its weight will be less. At the height of the summit of Mount Everest, anything weighs $1/500$ less than its weight at sea level. And if we go to a smaller world, gravity will be less because the world has less mass. On the Moon, for example, gravity is one-sixth of that on the Earth, and an astronaut has one-sixth of his Earth weight. But on Jupiter, a much larger planet than the Earth, he would weigh $2\frac{1}{2}$ times as much as on Earth.

If an object is thrown or fired up into the



The Earth's magnetic field tends to trap charged particles that reach us from the Sun, forming a great zone of radiation around the Earth called the magnetosphere. The solar wind, the stream of particles coming from the Sun, distorts its shape. In the large diagram, the solar wind is assumed to be coming from the left. Positively-charged protons are deflected as they cut through field lines (top inset), and spiral into the inner of the two radiation belts. Negatively-charged electrons spiral in the other direction and, being lighter, are more easily deflected. They enter the outer radiation belt (centre inset). Above the poles, the particles travel parallel to the field lines and are not deflected (bottom inset), reaching the atmosphere to produce the aurorae.

air, it will eventually return to Earth as gravity overcomes its outward motion. If it moves fast enough in a horizontal direction, it will go into orbit around the Earth and become a satellite. If the object is sent vertically upwards at increasing speeds, it will get farther and farther away before being pulled back to Earth. But there will come a point at which it escapes from the Earth's gravity and carries on moving through space. The velocity needed to do this is called the *escape velocity* and, for Earth, it is 11 kilometres a second. Spacecraft have to achieve this velocity to get to the Moon, for example.

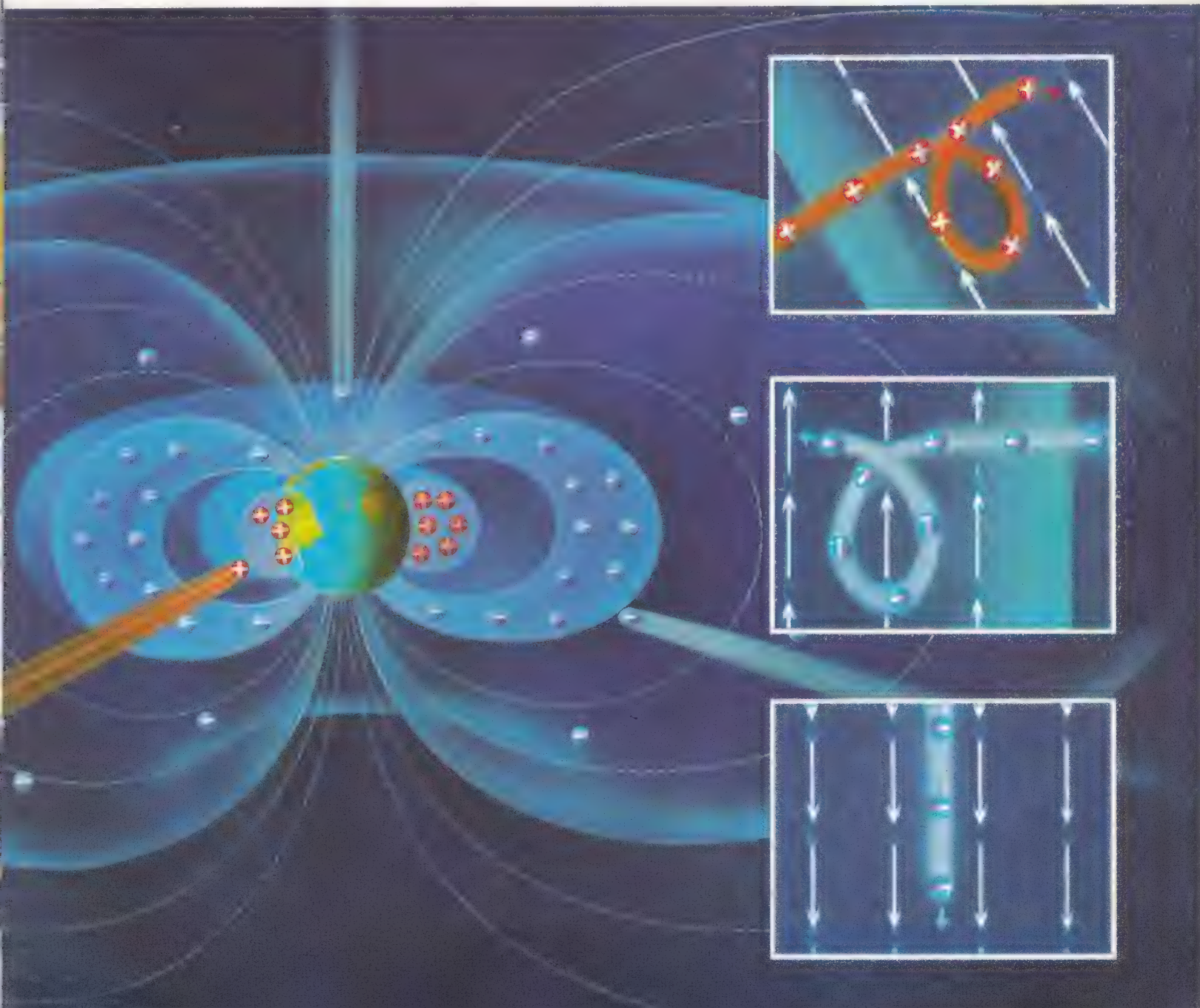
Black Holes

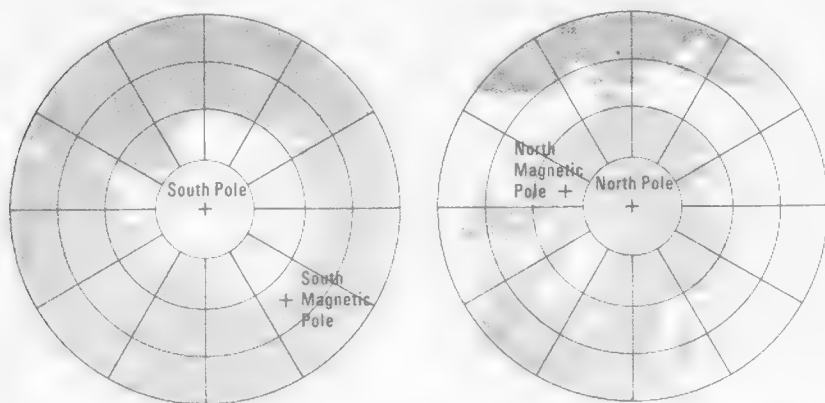
It is possible to think of a body that would have so much gravity that its escape velocity would be greater than the velocity of light. Nothing would be able to leave the surface of such a body, because nothing can travel faster than light. And light itself would be unable to escape too. Anything coming near would be pulled down to the body, including

light. Such an object is called a *black hole*, because it would suck up light and any object in its path. A black hole could not be seen, because it emits no light, but it could be detected by its effect on its surroundings. It is possible that a black hole has been found in the constellation Cygnus (the Swan) by satellites equipped with X-ray detectors.

To produce a black hole, a quantity of matter has to be compressed into a very small space. This might happen at the end of a star's life as it undergoes collapse. The Universe may therefore be populated with black holes, invisibly eating up all around them. It has even been suggested that one may exist at the centre of our Galaxy, slowly but inevitably gobbling its way towards us!

A black hole that is very massive need not be all that small. If a galaxy of a hundred thousand million stars could be compressed to a size fifty times greater in diameter than the solar system—which could be done without the stars touching—then the galaxy would become a black hole. On the other





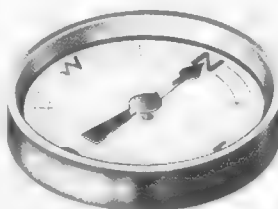
hand, a black hole of very small dimensions need not be very massive. If we could compress a block of iron weighing 1600 tons to one hundred-thousand-millionth of a centimetre in size, it would become a black hole, immediately sink to the centre of the Earth, and collapse our planet in a tremendous explosion. Fortunately, such a feat requires far more energy than we can produce.

If the expansion of the Universe is slowing, then the combined gravity of all the bodies in the Universe is acting to prevent anything from leaving the Universe. The Universe would then itself be a black hole, and we may be living inside one!

Magnetism

The invisible force with which magnets cling to or repel each other has long fascinated man. The ancient Greek philosopher Thales was the first man to study magnetism in about 600 BC, using pieces of the magnetic iron mineral called lodestone. Magnetic compasses were in use in Europe by about AD 1200, though the Chinese are believed to have noticed long before that a suspended magnet always points in the same direction. A magnet can be used as a compass because the Earth itself is a huge magnet and attracts the ends

Above: The two magnetic poles are located some distance away from the true geographic poles. The readings of a compass therefore have to be corrected by a few degrees, the precise amount varying slightly from year to year.



Above: A simple modern compass.

Below: An early mariner's compass. The magnetic compass began to be used in Europe in about 1200, but it developed in China about a thousand years before. The Chinese made spoons of lodestone and noticed that when spun, they often came to rest pointing in the same direction.



of the magnet, pulling them in a north-south direction. The end of the magnet that points north is called the north pole and the other end is the south pole. All magnets, however large or small, always have two different poles. Physicists have tried to find a magnetic monopole, a single pole on its own, but so far without success.

It is a basic law of magnetism that like poles repel and unlike poles attract each other. North attracts south and *vice-versa*, but north always repels north and south always repels south.

The metals iron, nickel and cobalt and their alloys are the only materials that are strongly magnetic. This is because they contain minute regions of magnetism like tiny magnets. These regions, called *domains*, can line up so that all their north poles point one way and all their south poles the other, giving a north pole at one end of the magnet and a south pole at the other. This can be done by subjecting the piece of iron or other magnetic material to a magnetic field, either by stroking it with another magnet or placing it inside an electric coil. Electric currents produce magnetic fields, a subject of great importance that is dealt with on pages 118-21.

The presence of a magnet is sufficient to make another piece of material magnetic; it simply lines up the domains by a process called *magnetic induction*. This happens when a magnet picks up a trail of pins; each one in turn becomes a magnet that induces magnetism in the next one. To produce induction, a magnet must be surrounded by a magnetic field that can penetrate materials. The field is made up of invisible lines of force along which other magnets will align themselves. A magnetic compass lines itself up along the lines of force of the Earth's magnetic field. These lead to the two magnetic poles, which are located some distance from the true geographic poles. The readings of a compass therefore have to be corrected by a few degrees, the precise amount varying slightly from year to year.

The Magnetosphere

Domains are thought to be formed by tiny circulating electric currents within a magnet, and the Earth's magnetism is believed to be produced by large-scale currents moving within its interior. The lines of force extend out into space, forming a doughnut-shaped magnetic barrier around the Earth. This barrier is called the *magnetosphere*. It captures particles arriving in the solar wind from the Sun, producing belts of radiation high above the Earth. These are called the *Van Allen belts* and were discovered by the first American satellite, Explorer 1, in 1958. Astronauts either keep to orbits below the belts or travel swiftly through them on Moon flights. Above the poles, the barrier falls away and the particles can then enter the atmosphere. As they do so, they produce the beautiful displays of lights known as the *auroras*.

The States of Matter

All matter comes in different states - solid, liquid and gas. Water, for example, may exist as ice, liquid water or steam. Knowledge of the ways in which each state behaves is vital in making use of all materials.



Three States

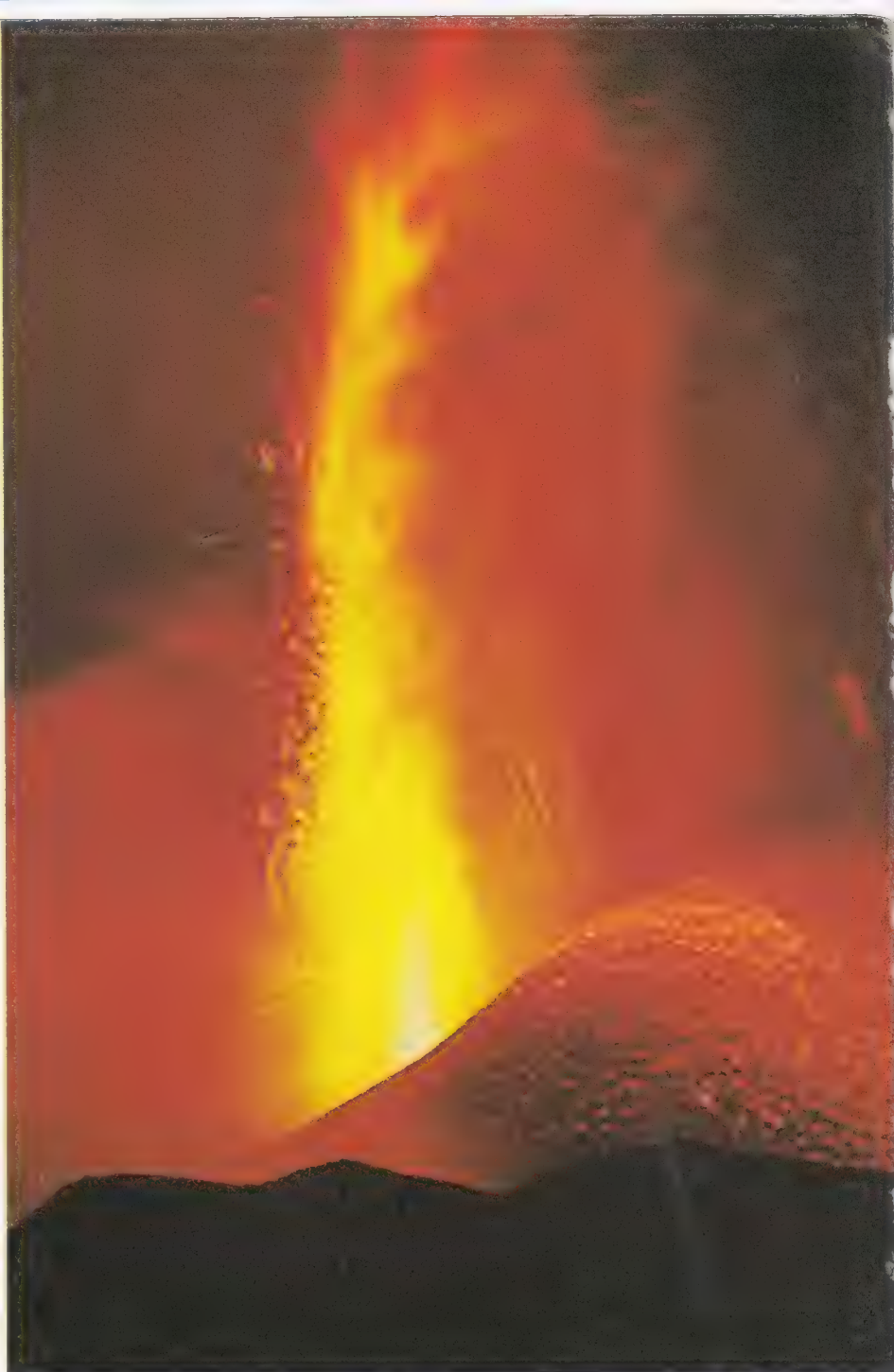
Why is it that rock should be solid, water liquid and air a gas? And how is it that every substance in the world, given the right conditions, can be changed into any of these three states of matter; that even the most solid rock will melt to a liquid in a volcano; and that the water vapour in the air will produce ice around the freezing compartment of a refrigerator?

The answer lies in the way that the molecules of a substance group themselves together. A molecule is made up of a set number of atoms tightly bound together, and the grouping of the atoms in each molecule does not change whether the substance is a solid, liquid or gas. But the grouping of the molecules within a solid, liquid or gas is very different. And to understand why this is so, we must look at the forces that bind molecules together.

Intermolecular forces are electromagnetic in nature and they are the forces that account for most of the effects we notice in everyday life. When two molecules lie alongside each other, they experience no force at all. If they get closer and begin to penetrate each other, the electric charges in the electron shells of the atoms repel each other and the molecules are pushed apart. They therefore move away from each other. However, when they get a little distance away, they experience an attracting force that pulls them together again. This force is produced by movements of the electrons in the shells. The molecules therefore constantly move to and fro, vibrating rapidly about the point where they lie alongside.

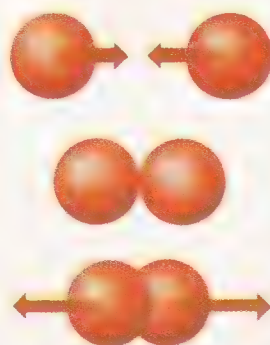
In a solid, all the molecules are vibrating in this way throughout the solid. The forces connect them together to give a lattice made up of regular rows of vibrating molecules. In a liquid, the molecules still vibrate, but in small clusters rather than one great network. Each of the clusters moves about in the liquid. A gas is different again. Here the molecules are much farther apart—on average about ten times the distance of the molecules in liquids and solids. This distance is greater than that at which the attracting force can pull the molecules together, and they move about at random at a speed of about 100 metres a second. Here and there they will collide with each other, but the rate at which the molecules collide is ten thousand times less than that at which they vibrate in solids and liquids. Even so, collisions between gas molecules are frequent; in air at freezing point, 10,000 million collisions are experienced by a molecule every second.

We can see now why a solid is hard and



Above: In a volcano, solid rock melts to a liquid and liquids boil explosively.

Below: Molecules continually vibrate about a central position (centre). Forces pull them together when they are apart (top) and push them apart when they penetrate one another (bottom).



KINETIC THEORY

The kinetic theory is an important theory in science because it assumes that matter is made up of molecules and that the behaviour of matter can be explained by this assumption. It assumes that molecules vibrate or move more quickly the hotter a substance is. The theory easily explains changes of state. As a solid is heated, its molecules vibrate more and more until its rows of molecules break up into clusters; that is, it melts. As the liquid is heated, there comes a point where the molecules in the clusters vibrate so much that the clusters break up and every molecule moves about on its own; that is, the liquid boils to produce a gas. However, molecules may break free from the clusters in the liquid before it boils and join the gaseous state; this happens in evaporation. Also, a moving gas molecule may be cooled so much that it slows its movement and joins the liquid state or possibly even the solid state. These changes of state are called respectively *condensation* and *sublimation*.

unchanging in shape; why a liquid will flow into the shape of its container; and why a gas will occupy any space that it is given. The rows of molecules in a solid are impenetrable and to change the shape of a solid involves cutting the forces that bind the molecules together. As these forces are strong and not easily overcome, a solid has hardness and shape. In a liquid, the clusters of molecules easily move and a liquid will therefore flow and take up any shape. And in a gas, the individual molecules fly everywhere; the gas fills a container and objects move easily through the gas.

Change of Phase

Each of the states of matter is known in science as a *phase*. Every substance can exist in any of the three phases, depending on its temperature and pressure. If a solid is heated, its temperature will rise and it will eventually melt. Heat the liquid and it will boil and become a gas. If a gas is compressed or cooled, its pressure will rise or its temperature will decrease; at some point it will become a liquid. Cool the liquid, and it will

THE AVOGADRO CONSTANT

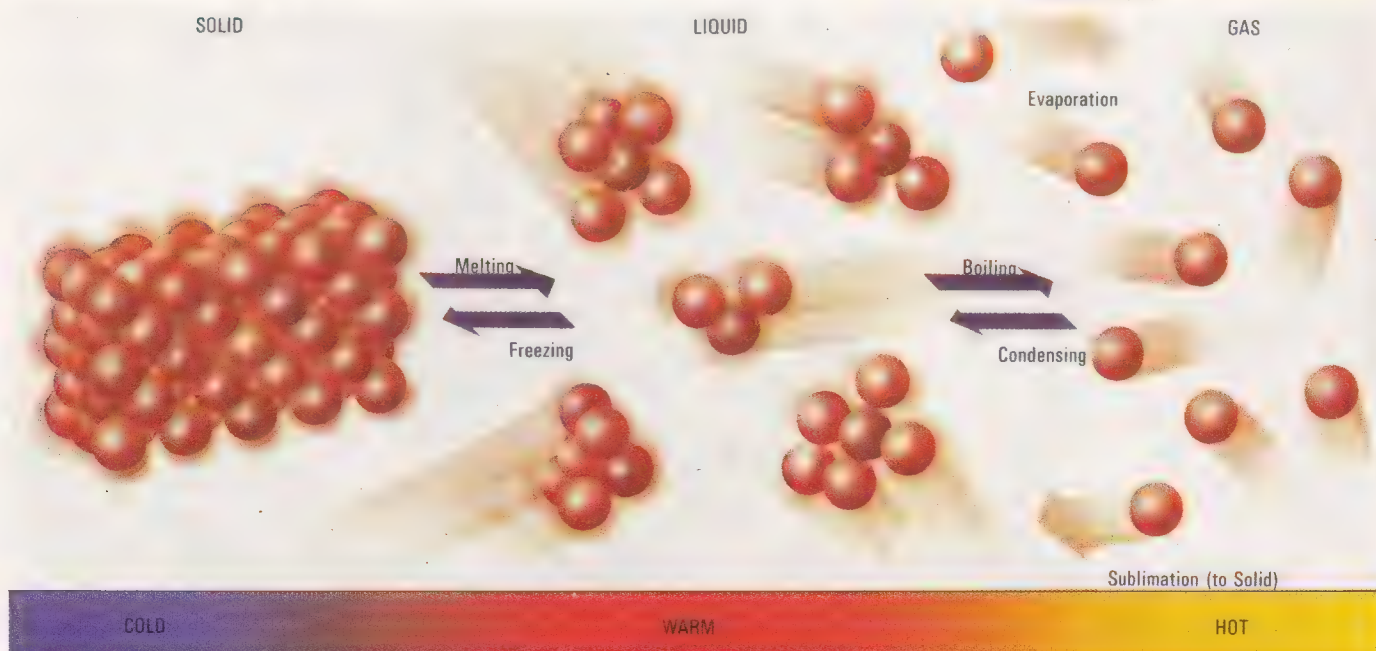
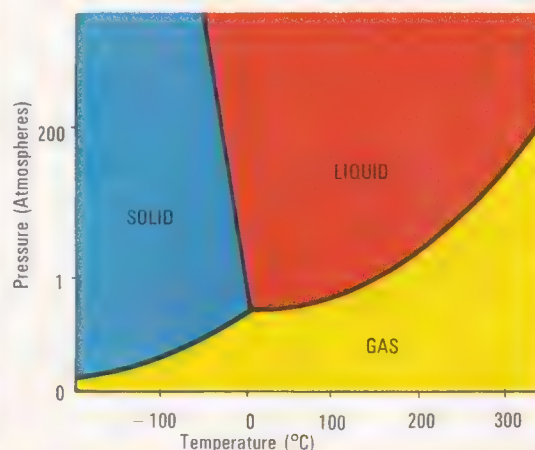
The SI unit of quantity is called the mole (symbol: mol) and is the amount of substance of a system which contains as many elementary entities as there are atoms in 12 grams of carbon-12. It is important that the nature of the elementary entities should be specified. They may be atoms, molecules, ions, electrons or other particles or groups of particles. The relative molecular mass in grams of a substance contains one mole of particles of that substance. Thus a mole of oxygen molecules (O_2) has a mass of 32 grams because the relative molecular mass of oxygen is 32. The number of entities in a mole is 6.02×10^{23} or 602 thousand million million and is called the Avogadro constant after the Italian scientist Amadeo Avogadro (1776-1856).

freeze to a solid. Every substance has its own melting or freezing point and boiling point, and may be identified by measuring the temperature at which it changes phase. Some substances do not melt but go directly from solid to gas and back again. This change of phase is called *sublimation*; and it is shown by iodine and carbon dioxide. Also, liquids change into gases below their boiling points; this kind of change is called *evaporation*.

SOLIDS, LIQUIDS AND GASES

The three states of matter are different because their molecules are arranged in different ways. The rows of molecules in a solid can be thought of as being like rows of soldiers drawn up on parade; they will move as a block but not individually. It is impossible to walk through the rows, just as one solid cannot penetrate another. In a liquid, the molecules are in moving clusters, rather like the couples on a dance floor. One can walk through the dancers with some difficulty, just as an object moves slowly through a liquid. The molecules in a gas are like people walking about in a big railway station; they move in all directions and occasionally collide. They take up the entire space of the station but it is easy to walk in any direction, just as a gas fills its container and offers little resistance to moving objects.

A phase diagram shows which states of matter exist at various temperatures and pressures. This diagram is for water.

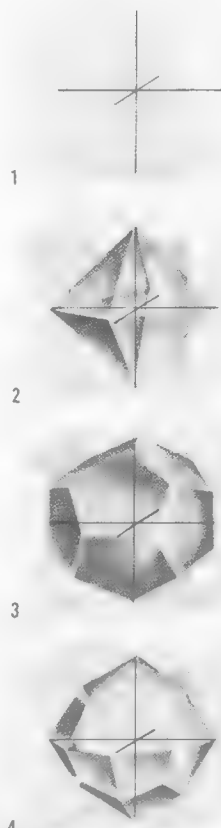


The Solid State

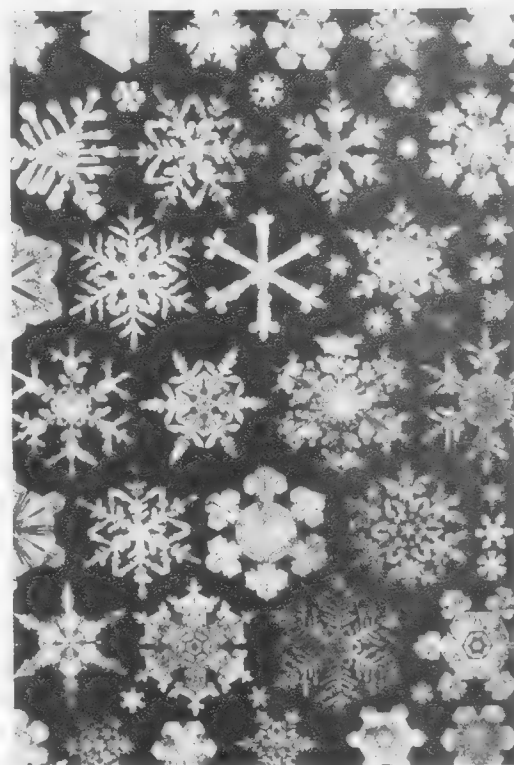
Crystals always excite interest; their perfection of form is unusual in the natural world, where things usually take any shape. In fact most pure solid substances are crystalline, but do not appear so because they are made up of masses of tiny crystals stuck together. Powders and rocks are two examples of such solids. Some things that appear to be solid, such as glass and resin, are not really solids at all but are best described as congealed liquids. They give themselves away on heating, for a true solid has a definite melting point. Congealed liquids get softer and softer on heating and do not melt at any particular temperature.

Crystals are remarkable because they are able to grow even though they are not alive. A small crystal of a substance will increase in size if it is surrounded by more molecules of the substance that are about to enter the solid state (this is done by cooling the liquid substance or strengthening a solution of it). As the molecules leave the solution or the liquid, they take up positions in rows so as to duplicate the rows of molecules in the crystal. The arrangement of the rows gives the crystal a certain set shape, however large it grows. The ordered arrangement of the molecules means that if the crystal is broken, then the pieces will always be smaller crystals and never fragments of a crystal. Crystals form in six basic forms or systems, though one of them is sometimes considered as two separate forms to give seven crystal systems. However, the particular system that a crystal occupies may not always be obvious because corners may be missing from the crystal.

Scientists do not have to grow crystals to find out how the molecules are arranged inside a solid. If a beam of X-rays is passed through the solid, the rays glance off the rows of molecules at various angles and emerge to



4 Minerals within the same crystal system may look unlike but still possess the same kind of symmetry. The cubic system has three equal axes at right angles (1), and many crystals in this system are cubic in shape. But by cutting corners from the cube, other shapes occur. An octahedron is first obtained, as in gold crystals (2), and then more complex shapes, as in pyrite (3) and leucite (4).



Water crystallizes in the hexagonal system, forming hexagonal ice crystals in complex branching shapes. The crystals mass together to form snowflakes.

give a particular pattern on a photographic plate. This process is called *X-ray diffraction* and the exact spacing of the molecules can be determined by examining the patterns. It is a useful tool to scientists. The arrangement of atoms within DNA was found by X-ray diffraction and with it came a new understanding of how heredity works. (The X-ray photographs taken in hospitals are different and just show the shadows made by bones, which block the X-rays more than the surrounding flesh.)

What Holds A Solid Together

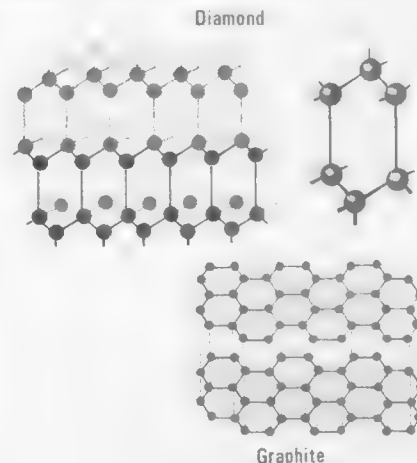
We have shown that a solid has hardness and shape and is generally held together by the forces that knit the molecules together into a network or lattice of identical rows. This is a

ALLOTROPES AND POLYMORPHISM

Polymorphism comes from Greek words meaning 'many shapes'. The bonds that hold atoms together in crystals may sometimes angle themselves in different ways so that a substance may take up more than one crystal form. When this occurs in elements, the different forms are known as allotropes. Although chemically similar, their molecules may contain different numbers of atoms—as in oxygen (O_2) and ozone (O_3)—and their physical properties differ. Physical differences are the result of differences in lattice structure. Both diamond and graphite are allotropes of carbon. In diamond, the carbon atoms are linked to other carbon atoms by four equal bonds. The network of bonds is very strong, making diamond extremely

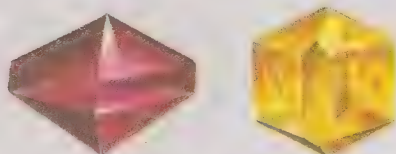
hard. In graphite, the atoms form planes in which each atom is linked to its neighbours by three bonds. A fourth weaker bond extends on each side of the plane, so that adjacent planes of atoms are held weakly together. The planes can slide over each other, making graphite soft and slippery. These properties are reflected in their uses, diamond being used for drill heads because of its hardness and graphite being used as a lubricant.

Compounds also exhibit the same kind of difference in structure and physical properties without any chemical difference. This effect is called polymorphism. Calcite and aragonite are two different crystal forms of calcium carbonate, for example. Mercuric iodide changes colour from red to yellow on heating because it changes its crystal structure.

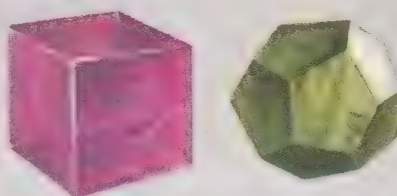


CRYSTAL SYSTEMS

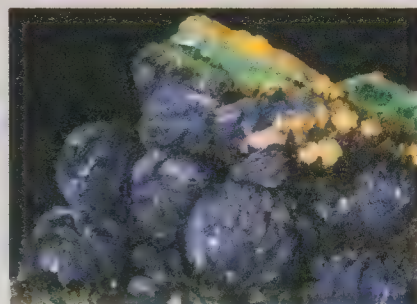
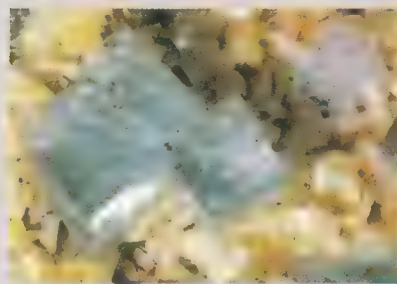
Although crystals may appear to come in all kinds of shapes, this is because they are often composed of clumps of smaller crystals. In fact, there are only a few basic shapes. These shapes are classified on the basis of their axes of symmetry, for the rows of atoms or molecules in a crystal, and therefore the faces, always align themselves with an axis of symmetry.



Tetragonal System. There are three axes each at right angles to each other, but only two are the same length. Examples are zircon (above left), rutile, tin, scapolite (above right) and chalcopyrite (below with small dolomite crystals).



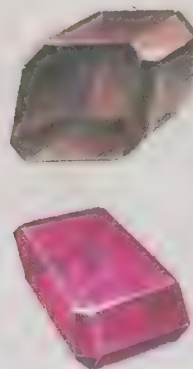
Cubic or Isometric System. There are three axes of equal length at right angles to each other. Examples are sodium chloride (salt), fluorite or fluorspar (above left and below), galena, alum, pyrite (above right), and many metals. The crystals often look like cubes or octahedra.



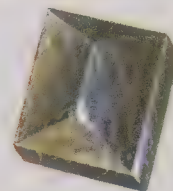
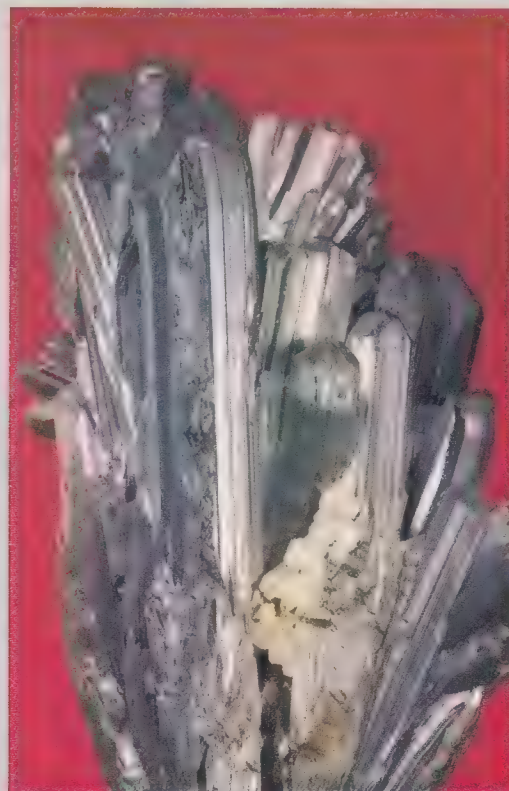
Monoclinic System. Two of the three axes are not at right angles but the third is at right angles to the other two; all three axes are of different lengths. Examples are blue azurite and green malachite (above), borax, gypsum, augite (below left) and realgar (below right).



Triclinic System. There are three axes, none of which meet at right angles and none of which are of equal length. Examples are auxinite (left above), rhodonite (left below) and albite (below).

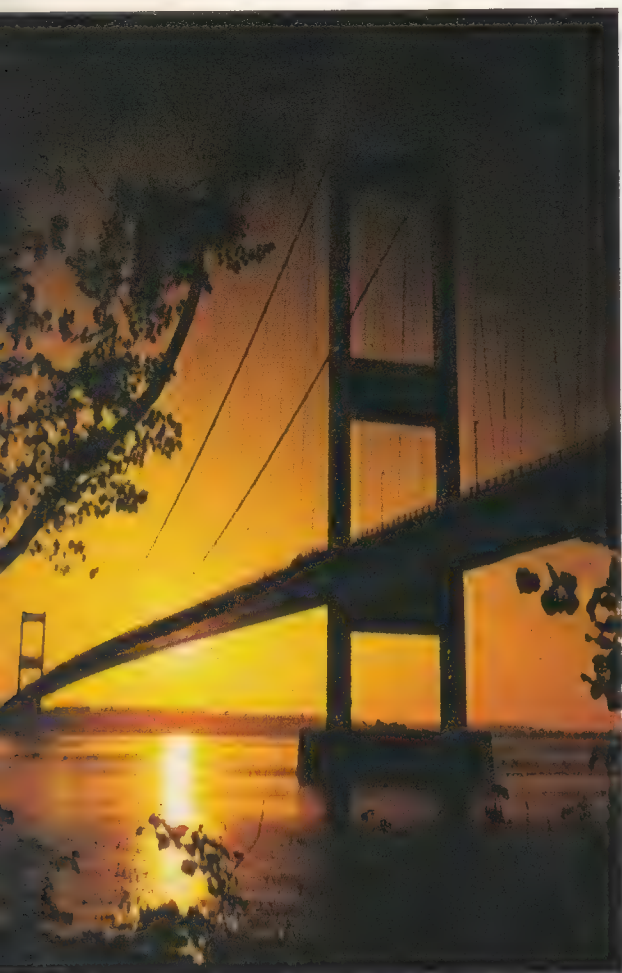


Hexagonal System. There are four axes, three of which are equal in length and meet at 60° . The fourth axis is at right angles and is of unequal length. The crystals are often six-sided. They include apatite (right above), zincite (right below) and red cinnabar and white quartz (below).

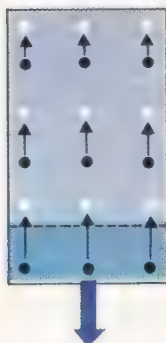


Orthorhombic System. There are three axes each at right angles to the other two; all three axes are of different length. Examples are staurolite (above), chrysoberyl (below) and stibnite (left).

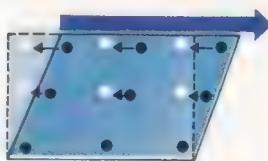




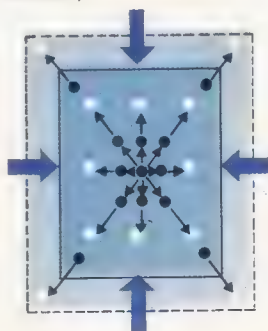
The behaviour of materials under stress must be known when a structure such as a suspension bridge is built.



Tensile Stress stretches a body. The molecules or atoms in the lattice are pulled from their original position (white) to a new position (black), but the attracting forces between them oppose the force stretching the body. When the stretching force is removed, the attracting forces restore the body to its original shape. The strings of musical instruments vibrate in this way. This kind of elasticity is measured by Young's modulus of elasticity.



Shear Stress twists a body out of shape, endeavouring to divide it into layers. Attracting forces between the molecules restore it to its original shape. A diving board works by this kind of elasticity, which is measured by the shear modulus of elasticity.



Compressive Stress forces a body to reduce its volume. Repelling forces between the molecules restore its shape. Rubber heels on shoes and the cartilage between the bones of the spine make our lives more comfortable by undergoing this kind of elasticity, which is measured by the bulk modulus of elasticity.

together by molecular forces called van der Waals forces. The bonds are weak compared with those of other solids, and so molecular solids tend to be soft and melt at low temperatures or even sublime. Some plastics, iodine and dry ice (solid carbon dioxide) are molecular solids. Hydrogen bonds form between molecules in certain solids when an oxygen atom in one molecule is attracted to a hydrogen atom in a neighbouring molecule. Ice is an example, and the helical strands in DNA molecules are held by hydrogen bonds. The bonds are electrostatic but not strong, so the solids are not tough and melt easily.

Using Crystals

Crystals have many uses in modern industry. They are particularly valuable because of their electrical properties. Transistors and other miniature electronic components are made of crystals in which the lattice structure has been carefully modified so that the movements of electrons through it can be controlled. Because the effects take place on an atomic scale, these components can be made as small as is physically possible and still work perfectly.

Piezoelectricity is another electrical effect found in crystals. If certain crystals are twisted, they give out an electric current. This effect is made use of in crystal pick-ups in record players. Piezoelectric crystals convert the vibration of the stylus into an electric signal.

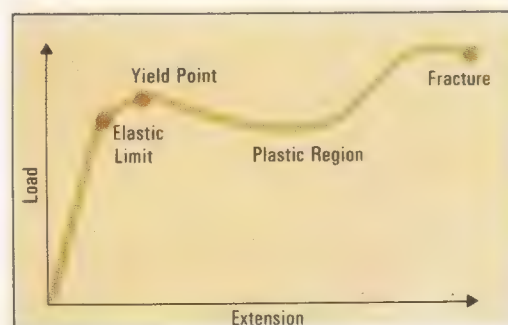
How Solids Behave

Solids might seem unlikely things to show any kind of behaviour, but the actions they perform in use are very important. The two factors that principally affect their behaviour are elasticity and hardness. A strong material is both elastic and hard.

Rubber bands are not the only things that are elastic; everything that is solid is elastic to some degree. If this were not so, the world would be a strange place. Everything would slowly change shape because all objects are slightly deformed when they are struck. Elasticity enables an object to regain its former shape.

A solid object can experience three kinds of force that will change its shape. It may be

A typical load-extension graph shows how a material stretches as it is loaded more and more. The extension is proportional to the load until the elastic limit is reached. Then the material stretches rapidly and unevenly until it fractures.



convenient picture but it is over-simplified. When we come to examine the nature of the bonds holding the molecules together, we must be more precise and confess that not all solids are made up of molecules. In fact, many consist of lattices of atoms rather than molecules.

There are five different kinds of bonding in solids. *Ionic* bonds form between atoms when one atom gives electrons to another. The two atoms become ions and have different electric charges, and they are then held together by electrostatic forces. Sodium chloride (common salt) is an example. In a salt crystal, sodium ions (Na^+) and chloride (Cl^-) ions are held in a cube-shaped network throughout the crystal. *Covalent* bonds form when atoms share electrons rather than make presents of electrons to one another. Diamond, which consists of carbon atoms held by covalent bonds, is an example. Both ionic and covalent bonds are strong, and crystals formed with these bonds are strong and have high melting points. Metals contain atoms in which some electrons are shared but do not belong to any particular group of atoms. Instead they wander about between the metal ions in the lattice. This is why metals conduct electricity. The metal bonds are less strong, so that metals can be fractured and melted more easily than ionic or covalent solids. Bonds involving electrons only utilize the outer electron shells of the atom.

Several solids do contain molecules bound

compressed and get smaller in volume; it may be twisted out of shape if a force is applied along one side; or it may be stretched and get longer if a force is applied to one end. But when the force acting on it is removed, the forces between the molecules or atoms in the lattice of the solid will make it spring back to its former size and shape.

Scientists talk about stress and strain when working on elasticity, but these terms have special meanings. Stress is the force acting on the object divided by the area of the solid on which it is acting. Strain is the change in size produced when an object is compressed or stretched divided by the original size or, when an object is twisted, the angle through which it twists. *Hooke's law* states that the stress divided by the strain is constant for any given material and this constant is called the *modulus of elasticity*. The size of the modulus gives a measure of how elastic the material is.

The degree of elasticity that a material possesses can be very important. The suspension systems of vehicles depend on elastic components to take up vibration, and the strings of musical instruments require a particular elasticity to produce a note.

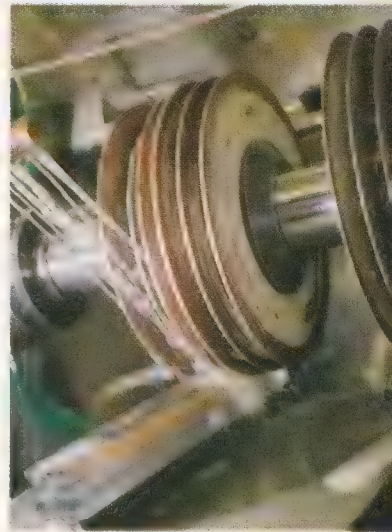
Elasticity will disappear if the force deforming an object is very great. If a wire is acted on by a steadily increasing force or load, it will continue to be elastic until the *elastic limit* is reached. Beyond this point, it will not regain its shape and become permanently deformed. With a little extra load, the wire reaches the *yield point*, after which it becomes plastic and small increases in load produce great increases in length. Finally, a constriction appears in the wire at a weak point and the wire soon snaps. Structures and materials must be thoroughly tested in this

way to find where the elastic limit lies, so that engineers can make sure that this limit is never reached when a structure is in use.

These changes occur because the increasing load makes the rows of atoms or molecules in the lattice slip and develop imperfections. In the plastic region, the rows slip over each other, and at fracture point, they simply come apart. Repeated flexing of a structure may cause this to happen suddenly, and such an effect is called *metal fatigue*. Not all materials behave in the same way. Brittle materials such as cast iron fracture on sudden stress before becoming plastic, and tough alloys such as hard steel and bronze do not reach a yield point before fracture.

Hardness is another important property to consider in engineering, for a soft material will be worn away by a harder material with which it comes into contact. Hardness is measured by the ability of one substance to scratch another, and every material is assigned a number between 1 and 10 on Moh's scale of hardness. Thus quartz (hardness 7) will scratch calcite (hardness 3) but will be scratched by diamond (hardness 10), the hardest known substance.

Materials can be made with varying degrees of elasticity and hardness. Metallurgists mix metals to produce alloys superior to their constituent metals, and various heat treatments during manufacture also affect their quality. Other properties may also be desirable. To be drawn into a wire, a material must be *ductile*, and to be hammered or rolled into a sheet, it must be *malleable*. In both cases, elasticity must be overcome during manufacture and hardness is a drawback, but great strength is still required in the final product.

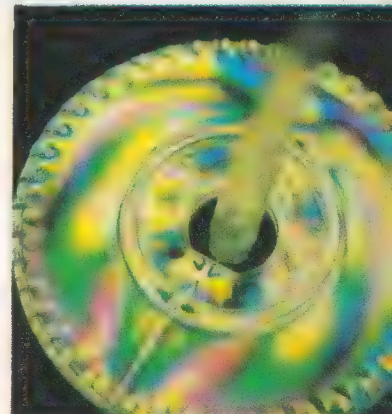


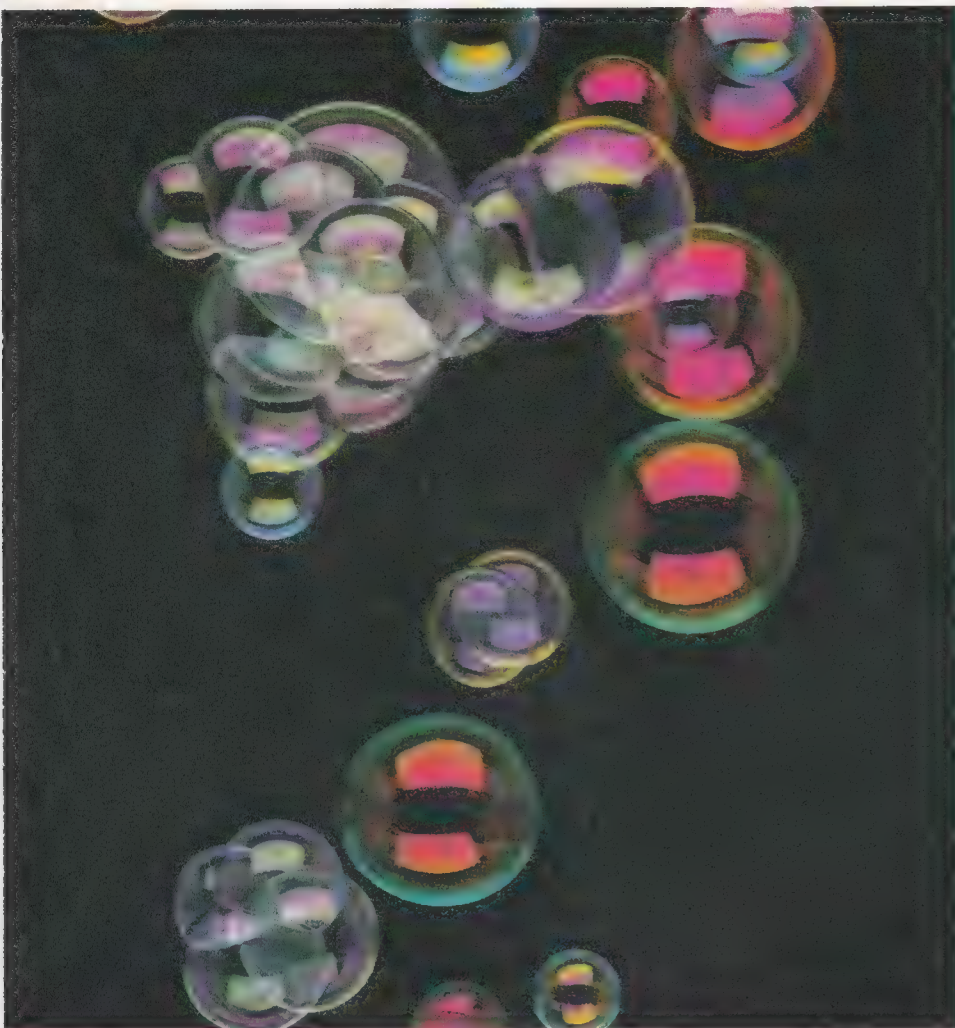
Diamond, being the hardest substance, is used to edge cutting wheels and tip drills. Cooled by water sprays, these diamond wheels are slicing their way through a quartz block.



Left: A complete airframe is continually flexed to simulate the stresses of flight, and find the point at which metal fatigue occurs. The airframe undergoes many more hours of testing than any aircraft flies.

Below: The distribution of forces throughout a plastic moulding produces a coloured pattern in polarized light, showing how the moulding will withstand stress.





LIQUID CRYSTALS

Halfway between solids and liquids, there exist substances that have their molecules arranged into set groups, like crystals, but which flow like liquids. These substances are known as liquid crystals. Because the arrangements of molecules are not completely fixed as in solids, they can easily be changed—for example, by an electric or magnetic field or by heat. The change in structure causes a change in optical properties, and a liquid crystal may change from transparent to opaque on receiving an electric or magnetic signal, or it may change colour when it is warmed or cooled. Liquid crystals may therefore be used to make the numbers that light up in clocks and calculators, and liquid crystal screens can show the heat distribution of a part of the body as a pattern of colours, which is very valuable in finding tumours. Other possibilities of liquid crystals include thin television sets that could be hung on a wall like pictures.

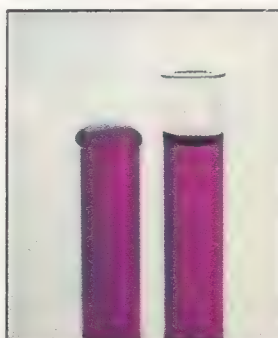


The Liquid State

As a solid melts to a liquid, the lattice structure is burst apart by the increased vibration of the molecules or atoms. Ionic bonds break, and the ions wander about through the liquid. Covalent bonds remain between the atoms within molecules, but molecules are only loosely associated and there is no particular order throughout the liquid as there is in a solid. Liquids do show some properties that are similar to those of solids. They are elastic under compression for the same reasons as solids are, but they flow and cannot be twisted or stretched.

Liquids, possessing no internal order, flow into any shape that they are given. Gravity pulls the molecules down and the liquid fills its container. But if gravity did not exist, what shape would a particular amount of liquid take? If we consider that all the molecules within the liquid attract each other equally, then they will pull the liquid into the most symmetrical shape possible, which is a sphere. This can in fact be seen in a drip of water falling from a tap. As it falls, it is free to take up any shape and so becomes spherical.

Surface tension pulls a soap bubble or a falling drop of water into a sphere. The surface of a tube full of water curves outwards for the same reason (left). But inside the tube, the water surface dips to form a curve known as a meniscus (right). This happens because the glass attracts the water sufficiently to overcome its surface tension, and pulls the water upwards where they meet.



Spacemen have to take care when using water because any free water, being weightless, breaks up into floating globules that are difficult to catch.

The molecules at the surface of a liquid differ from those inside. They are subjected to attracting forces from molecules below and beside them, but not above them. The forces produce a layer of molecules that acts like a skin on the liquid. This effect is called *surface tension*. It allows light objects, such as a needle, to 'float' on the surface of water. Some aquatic insects can skate rapidly across the surface by utilizing surface tension.

Cohesion and Adhesion

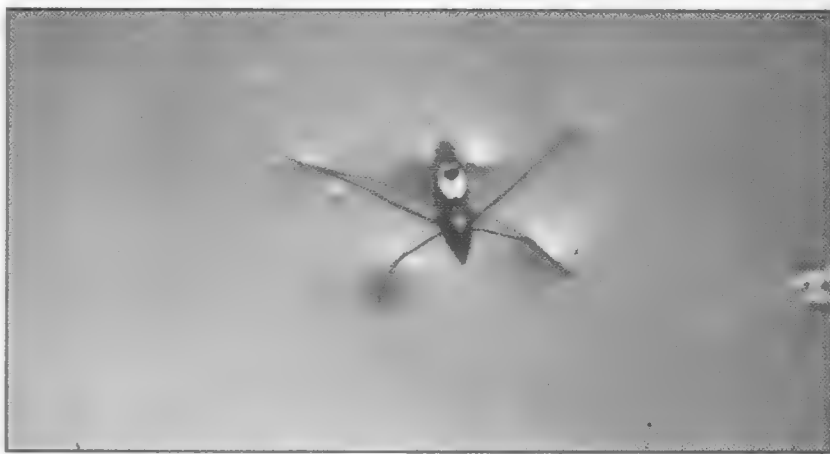
The way a liquid behaves when it comes in contact with the other states of matter depends on the strength of the forces between its own molecules and between its molecules and the molecules of the other state. The attraction between molecules of the same substance is called *cohesion*, and attraction between molecules of unlike substances is called *adhesion*. When a liquid meets a gas, the cohesion of the liquid is always greater than the adhesion between them. The liquid therefore pulls itself into a sphere if it is able to do so. But when a liquid meets a solid, either cohesion or adhesion may be greater. If you place some mercury on glass, the

mercury separates into little globules. Its cohesion is greater than the adhesion and it tries to get away from the glass and roll itself into spheres. If a glass tube of mercury is inspected, the surface curves down where it meets the glass for the same reason.

But when water is placed on glass, adhesion is greater than cohesion. The water molecules are more attracted to the glass molecules and the water spreads out over the glass, wetting it. The meniscus of water in a glass tube curves up because the water is attracted to the glass.

Adhesion is strong enough to be perceptible. Take two light flat objects, such as two lids, and place one on top of the other and then let go of the lower one. It will fall away. Now place some water on the lower lid and try again. It will stick to the top lid, and you can feel the adhesion of the water and metal pulling the lids together as you pull them apart. Take care not to let the lids slide apart.

Adhesion acts against surface tension because it destroys the naturally spherical shape of a liquid. If the liquid contains other substances with different shaped molecules, these substances will affect the surface tension. Detergents have long molecules and lower the surface tension of water, making it more



Above: A pond skater walks on the water, unable to penetrate the surface layer.

Below: Glass softens on heating, showing that it is not a true solid but a congealed liquid.



wetting and aiding cleaning. They also act to lower the adhesion between grease and fibres in the cloth being cleaned, so that the grease parts from the fibres.

If a tube is placed in water, water will rise a certain height up the tube. The narrower the tube the greater the height to which the water will rise. This effect is called *capillarity*, or *capillary action*, because it is best seen with capillary (very narrow) tubes. It is caused by surface tension, and the greater the surface tension of a liquid, the greater the rise. If cohesion exceeds adhesion, as in mercury and glass, the liquid will not rise but will sink in the tube.

Capillary action has important consequences. A flannel or towel soaks up water because it contains many fine pores that act as capillary tubes. Similarly, water seeps into bricks from outside a house and a damp course is inserted in walls and floors to prevent damp from the ground rising into the house in this way. Soil loses water by capillary action and hoeing breaks the passages along which the water flows so that roots may absorb the water instead.

Supercooling

Liquids can exist at temperatures below their freezing point if they are very pure. As a liquid cools, its molecules vibrate less and less and at freezing point, they begin to form into rows and make up the lattice of a solid. However, a small amount of a solid must be present to act as a nucleus at which lattice formation may begin. If the liquid is very pure and contains no solid matter at all, it may continue to remain liquid below the freezing point because lattice formation cannot get started. Introducing a tiny crystal of the same substance or perhaps simply a speck of dust or possibly even shaking the supercooled liquid may be enough to make it solidify. This effect is called *supercooling*.

Supercooling is important in rain and snow formation. Rain often forms in clouds that are below freezing because supercooled droplets of water exist in the clouds. The droplets produce water vapour that condenses on tiny ice crystals also present in the cloud. The crystals grow and eventually melt to produce raindrops, or they may fall as snow.

The Gaseous State

Unlike a solid or a liquid, a gas cannot be held in the hand and few gases can be seen; it is therefore a little difficult for us to feel that gases are as real as solids and liquids. We do not notice that all the time we are surrounded by an invisible mixture of gases—the air—that gives us life. It is only when we are having to battle against a high wind or recoil from a blast of hot air as we bend over an oven that we realize that gases can affect us just as much as the other states of matter.

There are as many different kinds of gases as there are different kinds of substances for, depending on its temperature, every substance has a gaseous state of matter as well as a solid and liquid state. Many gases are less unnoticeable than the colourless, odourless gases of the air and can immediately be detected by their smell, even in small amounts. The smell of rotten eggs that pervades the air around gas works is caused by hydrogen sulphide gas in the atmosphere. Some gases have colour too; chlorine can easily be identified (and avoided, for it is poisonous) by its green-yellow hue.

Gases are made up of individual molecules or atoms moving randomly through space at



Sir Robert Boyle (1627-91)

THE GAS LAWS

p = pressure
 V = volume
 T = absolute temperature

Boyle's law

$pV = \text{constant}$, if T is constant

Charles' law

$\frac{V}{T} = \text{constant}$, if p is constant

Pressure law

$\frac{p}{T} = \text{constant}$, if V is constant

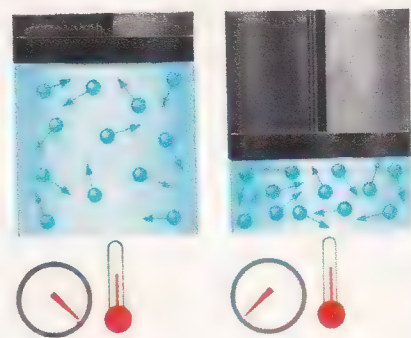
Equation of state

From the three gas laws, an overall equation of state can be derived that relates p , V and T . This equation, for 1 mole of gas (see page 47), is

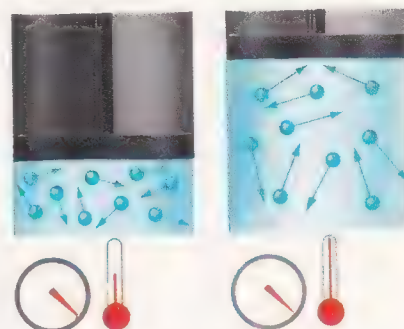
$$pV = RT$$

where R is the universal gas constant.

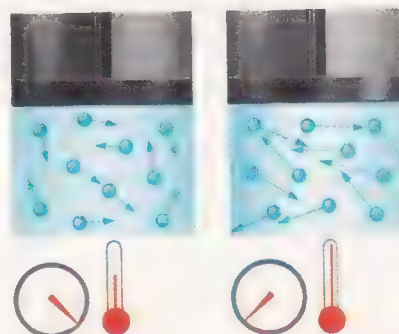
Left: The gases of the air move over the surface of the Earth as wind. This can exert sufficient force to move a yacht across water.



Boyle's law. The pressure of a given mass of gas doubles if its volume halves, provided that the temperature remains constant.



Charles' law. The volume doubles if the absolute temperature doubles, provided that the pressure remains constant.



Pressure law. The pressure doubles if the absolute temperature doubles, provided that the volume remains constant.

high speeds. Although the molecules or atoms are far too small to be seen, even with the most powerful kind of microscope, their behaviour can be detected by examining a particle of smoke through a microscope. Instead of floating steadily in the air (as a cloud of smoke does), the individual particles each zigzag about in a random way. The zigzag motion is caused by the gas molecules in the air continually striking the particle. The motion is called *Brownian motion* after the Scottish botanist Robert Brown, who first observed it in 1827. It was the first piece of evidence that atoms and molecules actually do exist, although Brown did not realize this at the time. Brownian motion can also be seen in particles floating in liquids, and Brown in fact first discovered the motion when he observed pollen grains suspended in water.

The Gas Laws

Every gas has three basic physical qualities—a certain pressure, volume and temperature. These three characteristics are related to each other by the gas laws. Pressure is inversely proportional to volume; that is, if the volume of a certain amount of gas is made smaller, its pressure will increase and vice-versa. This relationship is known as *Boyle's law*, named after the English chemist Sir Robert Boyle, who discovered it in 1662. It can easily be demonstrated by squeezing an inflated balloon; as the volume of the balloon is reduced, the pressure of the air inside increases until the balloon bursts. Volume and temperature are related to each other by *Charles' law*, discovered by the French physicist Jacques Charles in about 1787. This states that volume is proportional to temperature; that is, the more a gas is heated, the greater its volume and vice-versa. It can again be demonstrated with a balloon. If a half-inflated balloon is placed in the sun, it will expand as it gets warmer. From these two laws, a third law follows—the *Pressure law*. This states that temperature is proportional to pressure; the hotter the gas, the higher its pressure. In all cases, the third characteristic must remain the same, otherwise more than one law will come into operation at the same time. For example, pressure will increase proportionally with temperature only if the volume remains the same.

The gas laws are obeyed by ideal gases, but no gas is completely ideal and every gas deviates slightly from the gas laws because of the forces that exist between molecules. However, the gas laws do describe the fundamental behaviour of gases. They can easily be explained by the kinetic theory—the assumption that substances are made up of atoms or molecules. The pressure of a gas is related to the number of molecules striking the wall of the container and to the speed with which they strike the wall, and the molecules' speed depends on their temperature. If we squeeze a mass of gas into half its original volume, we shall have double the number of molecules striking the walls of its container in a given time and its pressure will double. If we double its absolute temperature, the molecules will move faster. If the volume of the container does not increase, the gas pressure will double; if the volume is allowed to increase until the original pressure is achieved, then the volume will double.

Mixing Gases

Gases easily mix together because the molecules of the gases can move among each other with no difficulty at all. This process is called *diffusion*; it also happens in liquids, though more slowly. We can smell a perfume from a flower because a small amount of gas from the flower diffuses through the air and reaches our noses. Gases may also diffuse through solid objects if they are porous and contain tiny holes. A tyre loses pressure after a while

because the air molecules inside slowly diffuse through the tyre walls.

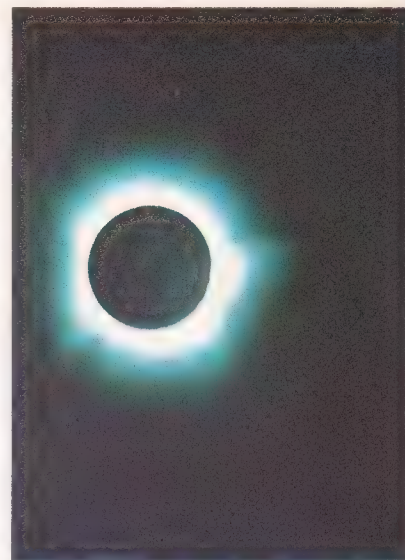
Gases and Vapours

The word 'vapour' is often used instead of 'gas' as if there were no difference between them, but this is not so. A vapour is a substance in the gaseous state, but if it is sufficiently compressed, the vapour will condense and form a liquid. However, above a certain temperature, called the *critical temperature*, a gas cannot be liquefied no matter how much pressure is applied. A vapour is therefore a gas below its critical temperature.

The critical temperature of water is 374°C —way above its boiling point. This means that the steam produced by a kettle is water vapour. In a pressure cooker, the pressure of the vapour is raised, and some liquid water remains in the cooker even though the temperature may be above 100°C , the normal boiling point.

Plasma

At the very high temperatures that exist in the Sun, a gas gains so much energy that the electrons become separated from the nuclei in its atoms. The great heat ionizes the atoms. This kind of gas is called a *plasma*, and it is sometimes considered a fourth state of matter. Scientists are experimenting with plasmas in an effort to find new ways of producing energy.



Above: The Sun is so hot that it is made up of plasma rather than gas. The heat separates electrons from nuclei, and drives beams of these particles out into space to form the solar wind.

Below: The feathery antennae of the male moon moth can detect the scent of a female moon moth over a distance of several kilometres. The scent vapour diffuses through the air to the male.



Fluid Pressure

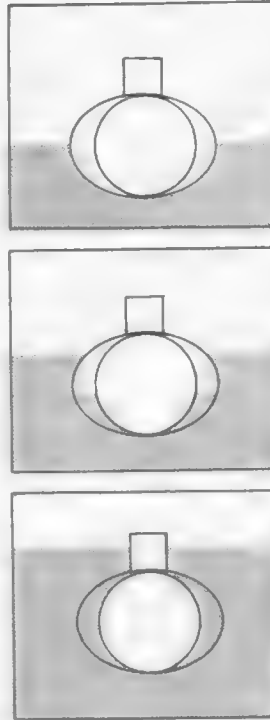
The children's story of the little Dutch boy who put his finger into a hole in a dyke and stopped the sea from flooding Holland could not, unfortunately, be true. The pressure of the water behind the dyke would overcome any effort the boy could make, no matter how hard he tried to stop the flow. If you place your finger over the end of a tap and try to stop the flow of water, you will discover that even the water supply has considerable pressure. Gases possess pressure too, and scientists use the term *fluid* to mean either a liquid or a gas. The pressure of the air pushes drink into your mouth as you suck at a straw, even though you may feel that your muscles are directly causing the action.

Fluid pressure plays an important part in our lives, but before we examine it more closely, we must look at a similar basic property that all substances possess—density. The density of a substance is simply the mass of a certain amount of it; water has a density of one gram per cubic centimetre, for example. Gases are very light and have low densities, and the density of the air is about a thousand times less than that of water. Most solids are more dense than water, lead having a density of 11.3 grams per cubic centimetre. Often, the terms *relative density* or *specific gravity* are used instead of density. These are simply the ratio of the density of a substance to the density of water, and have no units. Lead has a relative density of 11.3, for example.

Floating and Sinking

Why should a hollow vessel float on water, but sink to the bottom if it is holed and fills with water? And why should a block of wood float but a piece of lead sink? The answer lies in the densities of the objects and of water. When any object is submerged in a fluid, it displaces, or pushes out of the way, an equal volume of fluid. The volume of fluid displaced has a certain weight, and the fluid acts to push up the object with a force, or upthrust, equal to the weight of fluid displaced. This is known as *Archimedes' Principle*, because it was discovered by the famous ancient Greek scientist. As an object sinks into the fluid, it displaces more and more fluid and there may come a point where the upthrust of the displaced fluid is equal to the weight of the object. One force then balances the other, and the object floats in the fluid. However, this happens only if the object has a lower density than the fluid. If it is more dense, the object sinks into the fluid and falls to the bottom because the upthrust is not great enough to oppose its weight.

Wood floats on water because it is less dense and lead sinks because it is more dense



Above: Submarines have ballast tanks to vary their overall density so that they can sink or float. The tanks fill with water to counteract the submarine's buoyancy and sink. The water is pumped out when the submarine wishes to surface.

Right: A bottle will float in water because, being filled with air, its overall density is lower than that of water. But when it fills with water, its overall density becomes greater than that of water and it sinks.

Below: The Plimsoll line marks the deepest level at which a ship may safely float, and it must not be overloaded so that it sinks below the Plimsoll line. Fresh-water marks are to the left, and salt-water marks to the right. TF stands for tropical fresh water, F for fresh water, TS for tropical summer, S for summer, W for winter, and WNA for winter North Atlantic.



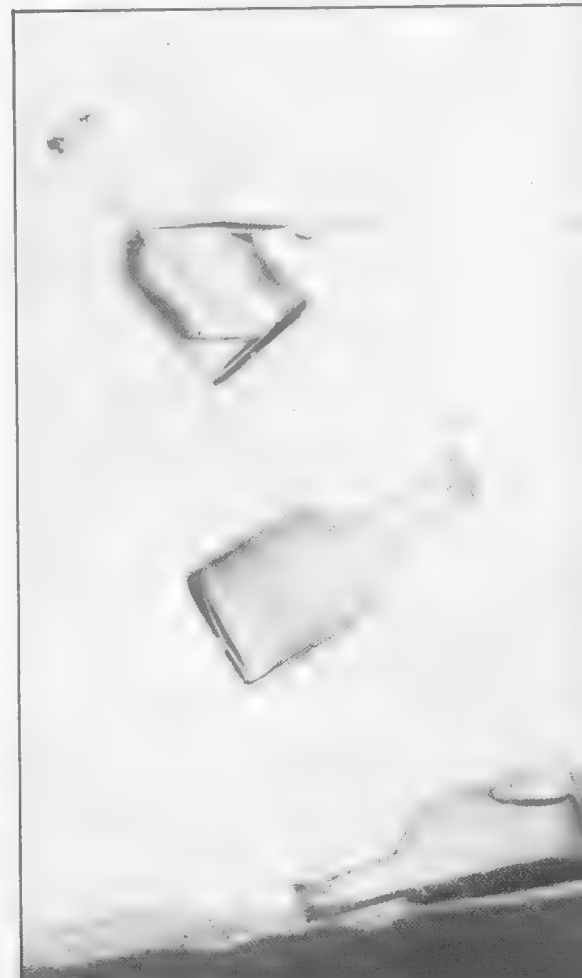
than water. A hollow object such as a boat, even made of a heavy metal, floats because its overall density is low as it is mostly filled with air. If the boat is holed and fills with water, its overall density becomes greater than that of water and it sinks.

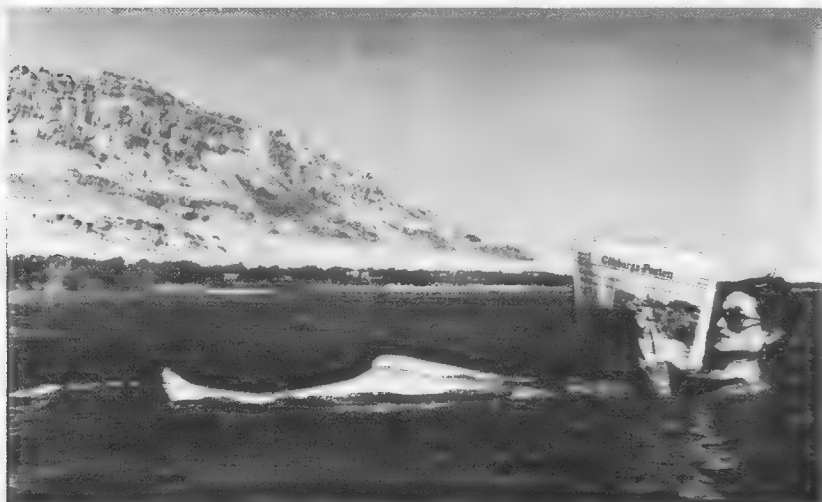
Air is a fluid too, but its density is so low that few objects can float in it. A hydrogen balloon is an exception, hydrogen being the lightest of all substances. A hydrogen balloon rises in the atmosphere until it reaches a level at which the air is so thin that its density is equal to the overall density of the balloon. This happens at a height of many kilometres, and hydrogen balloons are therefore used to carry instruments to high altitudes for research into the upper atmosphere.

A simple way of measuring the density of a liquid is with a *hydrometer*, which is basically a glass tube with a bulb at one end and a weight beneath. The instrument floats at a certain level in a liquid depending on its density; the lower the density, the deeper it floats. The density of the liquid is simply read from a scale on the tube.

Pressure and Depth

Gases and liquids can be compressed to obtain high pressures—road drills and the brakes on lorries and trains may be powered by compressed air. But every fluid possesses a certain pressure without being compressed. At any point in a fluid, all the fluid above that point will be pressing down on it and producing a certain pressure. The greater the depth in the fluid, the higher the pressure. The pressure is due to the weight of the fluid





An object that sinks in water may float in a denser liquid. The water of the Dead Sea is so salty that its density is greater than the overall density of the human body. People can therefore float with ease in the Dead Sea.



The pressure of the air can be strikingly demonstrated by placing a card over the top of a tumbler of water (left), turning the tumbler upside-down (centre) and taking your hand away (right). The card remains in place, because the air pressure beneath is greater than the pressure due to the water above it.

A dam has to be very strong to withstand the pressure of the water that builds up behind it. An arch dam is curved so that the pressure acts to compress the dam, giving it great strength.

ARCHIMEDES

Archimedes, who lived in Sicily (then a Greek possession) from 287 to 212 BC was one of the greatest scientists the world has seen. He was once given the problem of determining whether the king's crown was made of pure gold without damaging it in any way. Preoccupied with this question, Archimedes stepped into his bath without noticing that it was too full, so that it overflowed. However, he immediately realized that his body was displacing an equal volume of water and saw that immersing the crown in water would give a measure of its volume from the rise in water level. Then, by comparing the weight of the same volume of pure gold with the weight of the crown, he could find out whether the crown was made of pure gold or contained other less dense metals. At this realization, Archimedes is said to have run naked into the streets shouting "Eureka!" meaning "I've got it".

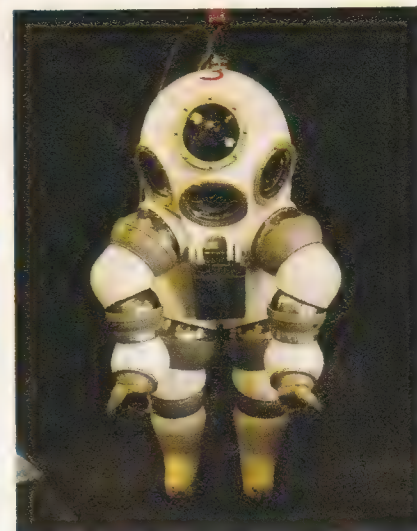
It turned out that the goldsmith had not used pure gold and was executed, but his crime was an unwitting aid to science, for Archimedes developed the principle of flotation from his thoughts on the subject.



above, and therefore also depends on the density of the fluid—the greater the density, the higher the pressure.

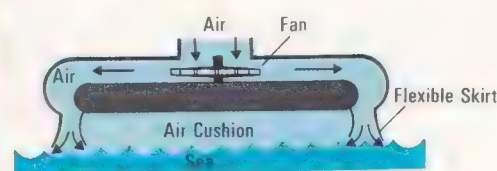
Water can produce an immense pressure by virtue of its depth. A diver endeavouring to breathe underwater by means of a long snorkel tube to the surface could get no deeper than two metres, where the pressure is already high enough to prevent him breathing naturally. For this reason, aqualung divers carry compressed air to overcome the water pressure. At the very deepest part of the ocean, the water pressure is 11,590 newtons per square centimetre—that is every square centimetre of any object or creature is subjected to a weight of more than a ton. Fishes and other sea creatures are able to survive such immense pressure because water is distributed throughout their bodies and the pressure is equalized inside and out. We experience the same effect, because we live at the bottom of an ocean of air. The air pressure is about ten newtons on every square centimetre of our body surface, producing a total weight over the body of about 20 tons. But because our lungs are filled with air at the same pressure, we feel no discomfort.

A *barometer* measures the pressure of the air and is useful in forecasting the weather, which is linked to changes in air pressure. A simple barometer can be made by upending a tube full of mercury into a dish of mercury so that



Above: A deep-sea diving suit is constructed of curved sections to withstand the immense pressure of the water at great depths.

Left: A small submersible enters the sea from its mother ship. It has a spherical cabin large enough for two.



Above: The hovercraft raises itself above the water on a cushion of high-pressure air. A flexible skirt at the side contains the air cushion.

Below: A large hovercraft driven by four airscrews races across the sea.

the open end is beneath the level in the dish. Provided the tube is long enough, the level inside the tube will fall to about 76 centimetres above the dish level. This is because the air pressure on the mercury in the dish is forcing the mercury up the tube, but it can support a column of mercury only 76 centimetres high. (For this reason, pressure is sometimes measured in centimetres or inches of mercury.) The Italian physicist Evangelista Torricelli first performed this experiment in 1643 and three years later, the French scientist Blaise Pascal sent his brother-in-law up a mountain in central France with a barometer (Pascal being too sick to go himself). He found that the mercury level fell as he ascended the mountain, showing that the pressure of the air decreases with height. This is to be expected, for the depth of the atmosphere is less at greater heights and so too is its pressure.

A similar effect happens whenever you suck up a drink through a straw. The action of the lungs lowers the air pressure in your mouth, and the greater air pressure at the surface of the drink forces it up the straw. A siphon works in the same way, air pressure forcing liquid into the siphon—though it will continue to flow only into a lower vessel.



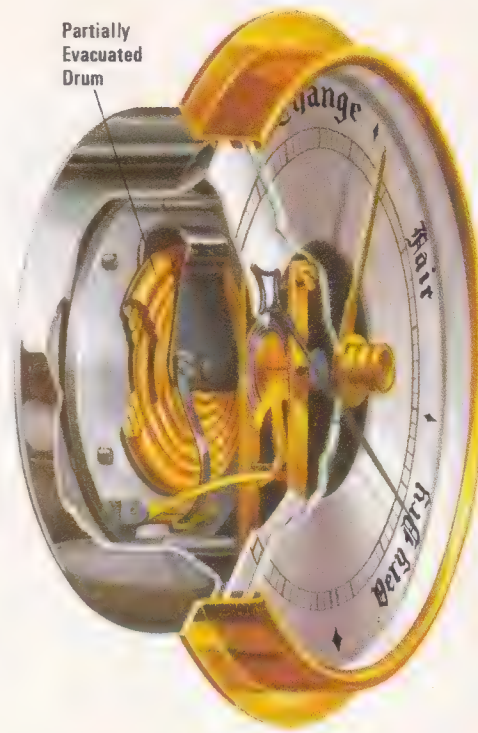
Hydraulics

Hydraulic systems are used to transmit power through pipes from a source of power to a point at which the power is to be applied. They work by fluid pressure, and are very convenient to use because a small amount of effort can produce a large amount of work. Braking systems, large presses and forging hammers, and mechanical diggers and bulldozers are operated by hydraulic mechanisms.

Basically, a hydraulic system consists of a pipe of liquid ending in a piston at each end. One piston is small and the other large. Effort is applied to the small piston, pushing it into the liquid and creating pressure throughout the liquid. This pressure then causes the large piston to move, thus transmitting the effort. The force produced is equal to the liquid pressure multiplied by the area of the piston, so the large piston produces a greater force than that exerted on the small piston depending on the difference in their areas. It will also move a shorter distance than the smaller piston, the difference also depending on the respective areas of the pistons.

Hydraulic braking systems are ideal for cars, not only because of the ease with which power can be transmitted but because the production of a single liquid pressure throughout the system ensures that all the brakes operate with exactly the same force and prevent skidding or wheel lock.

Right: The aneroid barometer measures air pressure. It has a partially evacuated drum that varies in width as the air pressure changes. The movement of the drum walls is transmitted through gears to the pointer, which moves round the dial to indicate the pressure. Another pointer is set by hand against the first and when the barometer is read later, the change in pressure can be seen. A move towards high pressure generally indicates good weather ahead, and a move towards low pressure bad weather.



Below: A hydraulic press shapes a white-hot bar of steel.

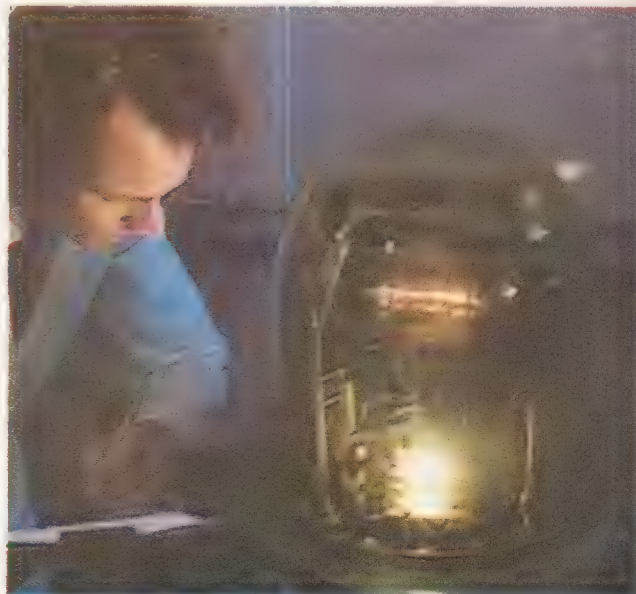


PRESSURE UNITS

A wide range of units exist to measure pressure. The SI unit is the pascal or newton per square metre, but scientists and barometers often employ centimetres or inches of mercury. Meteorologists use the millibar. Tyre pressure gauges show kilograms per square centimetre or pounds per square inch, and a vacuum is measured in torr. Engineers working with high-pressure vessels use the atmosphere as a unit of measurement. The following table shows normal atmospheric pressure in all these units.

101,325 pascals (newtons per square metre)
76 centimetres of mercury (cmHg)
29.92 inches of mercury
1,013 millibars
1.03 kilograms per square centimetre
14.72 pounds per square inch
760 torr
1 atmosphere

A film of gold is deposited on electrical contacts by vacuum deposition — introducing gold vapour into an evacuated chamber containing the parts.



VAPOUR PRESSURE

Liquids, and to a lesser extent solids, give off vapour into their surroundings, producing a certain vapour pressure. Any body of water produces water vapour and the hotter the water becomes, the greater the vapour pressure. When the vapour pressure becomes equal to the air pressure, the water boils, and all of the liquid water becomes water vapour. Because air pressure is less at great heights, water boils at a lower temperature high up in mountains.

The amount of water vapour that the air will hold depends on the temperature. When the air contains a maximum amount of water vapour, it is very humid. If the temperature should then fall, some of the water vapour condenses into water droplets and a mist or fog is produced. If it falls below freezing, a frost occurs.

VACUUM

A vacuum is a complete absence of anything and therefore has zero pressure. A vacuum flask is a vessel in which a vacuum lies between the walls; heat cannot readily cross a vacuum and so a vacuum flask retains heat (or cold). A television tube contains a vacuum because the presence of air inside it would block the beams of electrons that cause the picture to form. A complete vacuum is impossible to produce on Earth, because the walls of its container always give off a little vapour. A vacuum can be produced that is 10,000 million million times rarer than normal atmospheric pressure—however, this corresponds to about ten million molecules per litre. Even in space, a complete vacuum does not exist and about a thousand molecules occur per litre.

Fluid Flow



The flow of fluids within pipes and the motion of solid objects through fluids—either liquids or gases—have important consequences. The principles governing fluid flow must be understood in designing aircraft and parachutes, for example. A golfer trying to curve the flight of his ball by putting spin on it is making use of the principle of fluid flow, and so too is anyone who tries to paint a ceiling without covering themselves in paint. Two main factors govern fluid flow: the relationship between the velocity of the flow and the pressure of the fluid, and the viscosity of the fluid.

Velocity and Pressure

The Swiss mathematician Daniel Bernoulli founded the science of fluid flow or hydrodynamics. In 1738, he discovered the fundamental principle that the pressure of a moving fluid falls as the velocity of the fluid increases. This is known as *Bernoulli's principle*, and it has many important applications. It can be demonstrated by running water through a pipe containing a narrow constriction; as the water enters the constriction, its speed increases and pressure measurements show that its pressure falls. An instrument for measuring the speeds with which fluids move through pipes is constructed in this way, and is known as a *venturi meter*. It is simply a pipe with a narrow section and pressure sensors connected to the main body of the pipe and the narrow section; from the pressure difference between the two sensors, the fluid velocity can be calculated. Bernoulli's principle in fact follows from the law of conservation of energy. The speed of the fluid molecules increases as they enter the constriction and each molecule gains energy; however, the total energy of the fluid must remain the same and so the number of molecules in the constriction decreases—that is, the pressure falls.

Bernoulli's principle finds applications in many different fields. A Bunsen burner contains a jet of gas at its base and a hole through which air can be admitted to mix with the gas before it reaches the top of the burner and ignites. As the gas rushes from the jet, its pressure is reduced and air is sucked through the hole to mix with the gas. In the carburettor of a car, air passing through a narrow constriction in a tube meets a jet feeding petrol to the engine; the lowered pressure of the air in the constriction pulls

petrol into the airstream and the petrol-air mixture then goes to the engine.

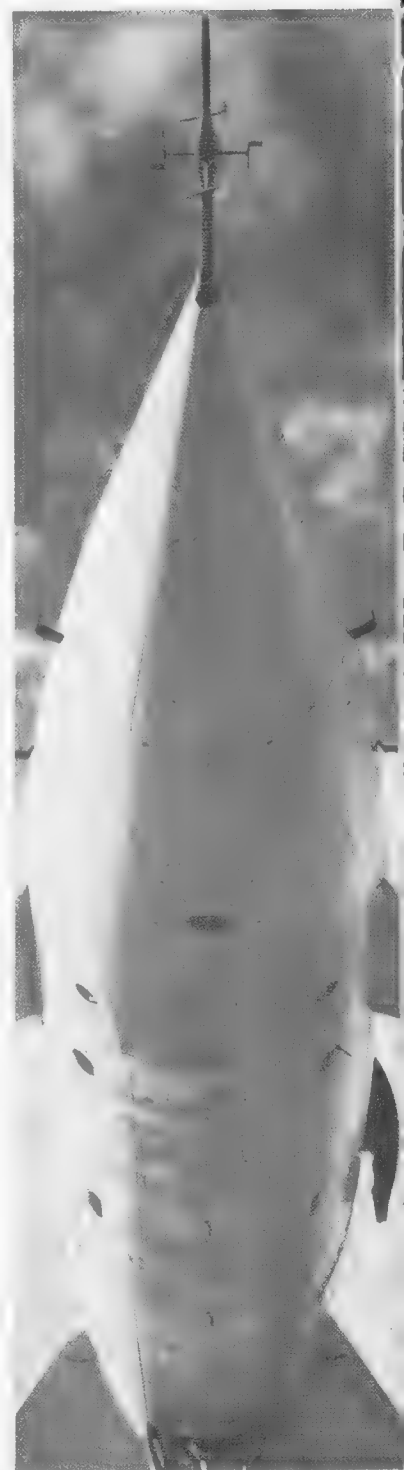
Bernoulli's principle applies to objects moving through fluids as well as to fluids moving through pipes. As a ball travels through the air—which is a fluid just as a liquid is—air will be diverted around it. If the ball is spinning, the side of the ball spinning in the same direction as the direction of flight will be moving faster than the side spinning against the direction of the flight. Each side will carry air with it, but the air at the first side will be moving faster than the air at the other side. The air pressure will therefore be greater at the slow-moving side than the fast-moving side, and the ball will be deflected by the difference in air pressure towards the fast-moving side. That is, the path of the spinning ball will curve—a fact known to golfers and many other sportsmen.

Flight, both powered and unpowered, is made possible by Bernoulli's principle. The cross-section of a wing, or an aerofoil, is shaped so that air is diverted a greater distance over the wing than beneath it as the wing moves through the air. The air passing over the wing therefore has to travel a greater distance than that passing beneath; it therefore moves faster and, by Bernoulli's principle, its pressure falls. A greater air pressure will therefore exist beneath the wing, and acts to push up the wing and lift it. This is how birds, gliders, aircraft, boomerangs and paper darts fly. Racing cars have aerofoils that are fixed upside-down above the tail of the car to produce the opposite of a lift and force the car down, giving greater adhesion to the road surface.

Viscosity

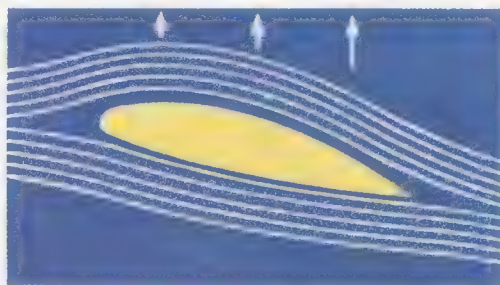
As an object moves through a fluid, it meets resistance to its motion and will be slowed down. The *viscosity* of a fluid is a measure of its resistance to the movement of objects through it, and also to its own movement. A highly viscous liquid, such as syrup, flows very slowly when poured whereas water, having a low viscosity, flows rapidly. Air has a low but detectable viscosity; you can feel this every time a wind blows in your face.

Anything moving through a fluid will reach a constant velocity that depends on the force moving it and on the viscosity of the fluid. This velocity is known as the *terminal velocity*. An aircraft travels at a constant speed



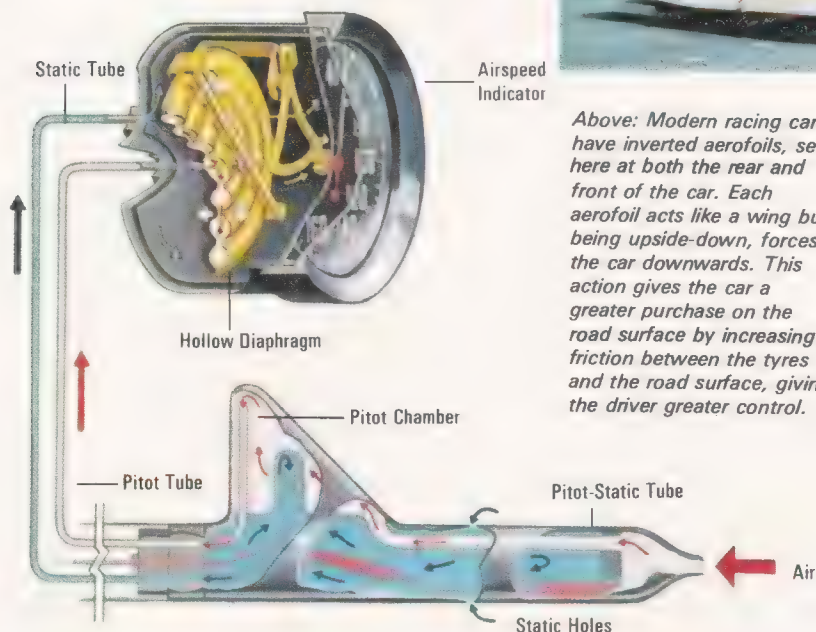


Flying objects, from birds such as swans (opposite page) to supersonic airliners (above), all depend on the aerofoil (right), usually as a wing, to keep them in the air. Air flows faster over an aerofoil than beneath it. Air pressure falls above the aerofoil and the air below forces it upwards.



Opposite page: The nose of the supersonic airliner Concorde narrows to a point to produce the least resistance to motion through the air.

Below: The airspeed of an aircraft is detected with the pitot-static tube, which is situated in the nose or wing of the aircraft. Air rushes into the pitot chamber, setting up a high pressure in the pitot tube. This tube is connected to a hollow diaphragm and the high air pressure expands it. The expansion of the diaphragm moves the pointer on the dial of the indicator. The diaphragm is surrounded by still air at a low pressure led from static holes into the static chamber and through the static tube.



Above: Modern racing cars have inverted aerofoils, seen here at both the rear and front of the car. Each aerofoil acts like a wing but, being upside-down, forces the car downwards. This action gives the car a greater purchase on the road surface by increasing friction between the tyres and the road surface, giving the driver greater control.

when the force of its engine equals the drag of the resistance of the air. Sky divers reach terminal velocity in free fall when the pull of gravity equals air resistance. Increasing a faller's area increases resistance to his motion, so that pulling in the arms and legs enables him to fall a little faster; opening a parachute reduces the terminal velocity to one at which he can land safely.

Friction between a moving object and a fluid produces a rise in temperature as the fluid molecules gain energy from the motion of the object. This is seen dramatically in spacecraft as they re-enter the atmosphere. Friction with the air checks the spacecraft's headlong flight, but produces searing temperatures. The space mission would soon result in a fiery end, were it not for the heat shield at the base of the spacecraft that dissipates the heat of the friction with the air.

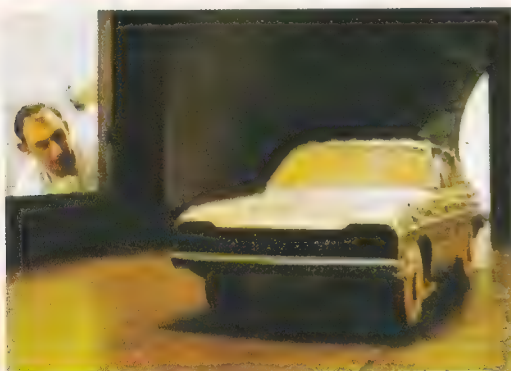
Viscosity is caused by friction within a fluid. As a fluid moves or an object moves through it, fast-moving layers are set up in the centre of the moving fluid or next to the moving object. These layers are called *streamlines*, and every molecule in a streamline moves in the same direction with the same velocity. However, the streamlines alongside move less

rapidly, so that a group of streamlines moving at different speeds are set up throughout the fluid. The molecules in one streamline attract molecules in the next streamline as they pass them; the attraction acts to oppose the motion and produces viscosity. Heating a liquid gives the molecules more energy and reduces attraction between them. In most liquids therefore, a rise in temperature lowers viscosity. This can be seen at breakfast if you spoon out some syrup from a jar on a cold morning; it will take a long time to pour from the spoon. If you then stir the syrup into some hot porridge, it will soon warm up and lower its viscosity, making stirring easier.

Gases are different from liquids in that there is less attraction between molecules,



Above: Sky divers reach a terminal velocity as they fall through the air. Spreading their arms increases air resistance and decreases their velocity.



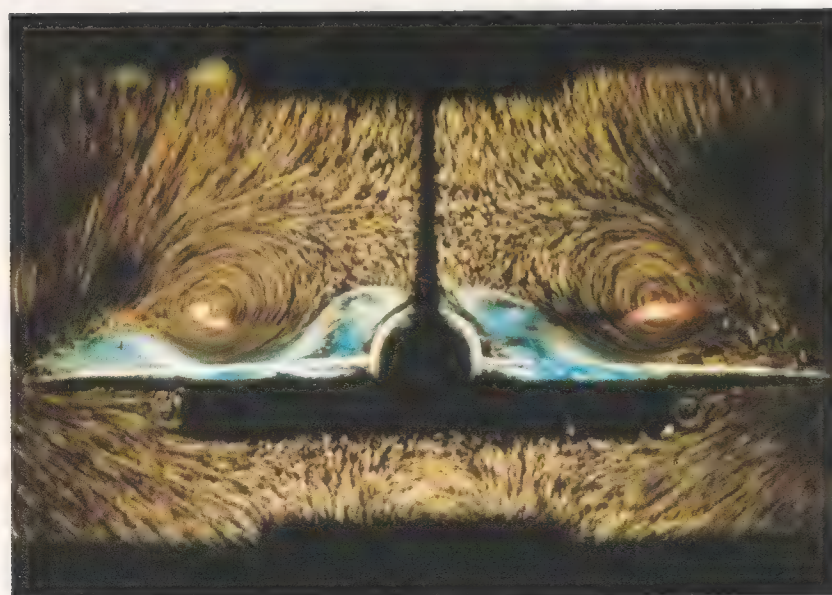
Left above: Car designers study the flow of air over a new car by placing a model in a wind tunnel.

Left below: In high-speed cars, streamlining reduces air resistance and helps to save fuel as well as raise speed.



Below: Wind tunnel tests show how air moves over the wings of an aircraft.

Below right: At high angles, the streamlines over an aerofoil break up and produce turbulence, causing a loss of lift (top). By opening a flap at the front of the wing, the streamlines are restored and lift is retained (bottom).

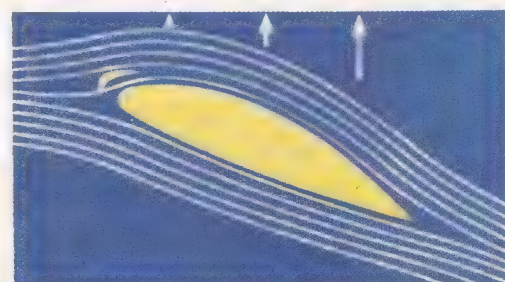
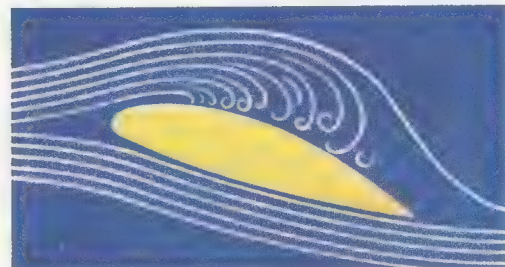


giving lesser viscosities, and the motion of the molecules is more random, so that some will cross the streamlines and impede their motion. This action is increased as the temperature rises, and so a gas has a higher viscosity when it is heated.

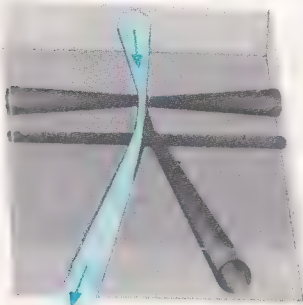
The viscosity of many materials varies with the direction and force of motion. A paint can be briskly brushed onto a surface and show low viscosity, making painting easy, but it will show a high viscosity once on the surface and subjected to less force—that is, it will stick and not flow.

Turbulence

When streamlines are set up through a liquid, its flow is smooth and even. An aircraft is streamlined to produce the least resistance to its motion through the air, and the airflow around it and over the wings will be made up of streamlines. However, at high speeds the streamlines may begin to break up and *turbulent flow* is produced; the molecules gyrate in an eddying motion. This can be seen by opening a tap. At first the water flows slowly and evenly and the flow is totally

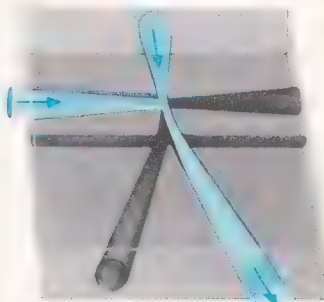


Right: A modern ship, seen here in dry dock, has a bulge beneath its bow to reduce the bow wave it creates as it moves through the water. This cuts down the energy wastage produced by wave making.



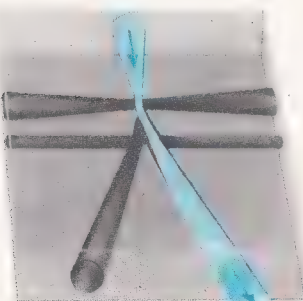
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If you just touch a stream of water from a tap with the curved back of a spoon, the stream will immediately be diverted to follow the back of the spoon. This is called the wall attachment principle, and it is used in a fluidic



2

device that acts as a switch. A main supply of fluid passes through the switch and is diverted into one of two output channels, constantly following the channel just as it would the back of a spoon (1). A brief jet of fluid arriving at the input on the same side as



3

the output (2) will switch the supply to the other output channel. The new output supply (3) will then go to a controller in a machine and alter the performance in some way. Brief input signals will switch the output supply to and fro as often as required.



clear; as the flow gets faster, the stream of water becomes uneven and its clarity disappears as turbulence occurs.

Turbulence is very important in flight. If the airflow over a wing becomes turbulent, then lift will be lost and the aircraft may stall and crash. The shape of the wing is very important in maintaining an even airflow, and flaps are opened and closed to vary the aerofoil shape and maintain lift at all speeds. Wind tunnel tests, in which accurate models of wings and aircraft bodies are subjected to a stream of air moving at various speeds, are essential to aircraft design.

Fluidics

Fluidics is a comparatively new branch of science that makes ingenious use of moving fluids on a small scale. Its basic principles are simple and concern the behaviour of streams

of fluids within channels of certain shapes. Controlling devices can be made for machines that use jets of fluid in the same ways as currents of electricity. Both act as signals, either as input signals from detectors that monitor a machine's performance or output signals that control the machine's production. Fluidics devices act like electronic components in switching and amplifying the signals so that the machine continues to work according to its programme. Compressed air is usually used as the fluid, so that fluidics systems can operate at high temperatures and when subjected to radiation—conditions under which electronic systems soon break down. They are also very robust and reliable. Fluidics therefore finds use in nuclear reactors and in space rockets, as well as in devices to control sliding doors, textile machinery and lathes.

Matter in Solution

Solids, liquids and gases are not always made up of pure elements or compounds. Mixtures and solutions of different substances, sometimes in different states of matter, are often to be found. A mixture of solids usually consists of fine grains closely intermingled—stirring salt and pepper together forms a simple mixture, for example. A fizzy drink consists of a mixture of liquid and gas (in the bubbles). Mixtures can easily be separated into their various constituents, but solutions cannot. A solution is such a thorough mixing of substances that the molecules of the different constituents intermingle, whereas in a mixture the different molecules are separated. All gases and many liquids mix so thoroughly that they form solutions, but some liquids will not dissolve in each other.

Solutions are vital to life. The substances we need for life originate in the food we eat, but are carried around the body as solutions in the bloodstream before we make use of them.

How Solutions Form

Any substance that dissolves another is called a *solvent*, and the substance that is dissolved is the *solute*. For example, when we put sugar in a cup of tea we obtain a sugar solution; the



Fishermen often voyage to the cold and dangerous waters of the Arctic in search of large catches. Cold water dissolves a greater amount of oxygen than warm water, and so the polar waters teem with fish and other marine life.

Air may look clean, but it is often polluted with colourless gases. Acidic gases in the air may dissolve in rain water to give a weak acid that slowly eats away such stones as marble. The statue shown below has become defaced in this way.



hot water of the tea is the solvent, and the sugar is the solute. A solution will form where the molecules of the solvent can overcome the forces binding the solute molecules together. In ionic substances, such as salt, solvent molecules attach themselves to the lattice of ions and weaken the electrical forces joining the ions so that they separate and begin to wander about in the solvent. When salt (sodium chloride) dissolves, water molecules separate the sodium and chlorine ions. In non-ionic substances, the energy of the solvent molecules overcomes the forces attracting the solute molecules to each other, and the solute molecules disperse among the solvent molecules.

The power of one substance to dissolve another therefore depends on their molecules; every solvent will dissolve only a certain range of solutes and no others. Substances that will not dissolve one another possess molecules that repel each other, so that they cannot come close enough to intermingle and form a solution.

Crystallization

When solids dissolve in liquids, the solution becomes stronger or more concentrated as more solid dissolves but there comes a point at which the solution is as strong as it possibly can be and no more solid will dissolve, however much is added. Such a solution is said to be *saturated*, and its strength depends on the temperature. With most solids, solubility (the amount that will dissolve) increases with temperature; the hotter a solution is, the stronger it can be made. If a saturated solution is cooled so that solubility falls or if some of the solvent evaporates from it, the solution will contain more solute molecules than it can retain in solution. The solute molecules will begin to link together and crystals begin to form in the solution. As evaporation or cooling continues, more and more solid will crystallize and the crystals formed will grow. Often, a small crystal or some small object has to be placed in the solution so that crystals may form on it, otherwise crystallization may not

THE BENDS

Divers must be very careful when operating at great depths. The pressure of the water around them increases the pressure of the air they breathe, and at great depths, the increased pressure causes nitrogen gas in the air to dissolve in the blood. This does no immediate harm, but as the diver returns to the surface the pressure decreases and the nitrogen begins to leave his blood. If he ascends too rapidly, the nitrogen forms bubbles in the bloodstream, producing a very painful condition known as the bends. Paralysis and death may occur in severe cases. A diver suffering from the bends must be placed in a decompression chamber, where he is subjected to a pressure equal to that at the depth where he was working so that the bubbles redissolve. Then the pressure is slowly lowered so that the nitrogen leaves the blood without forming bubbles. This may take several hours or even days.

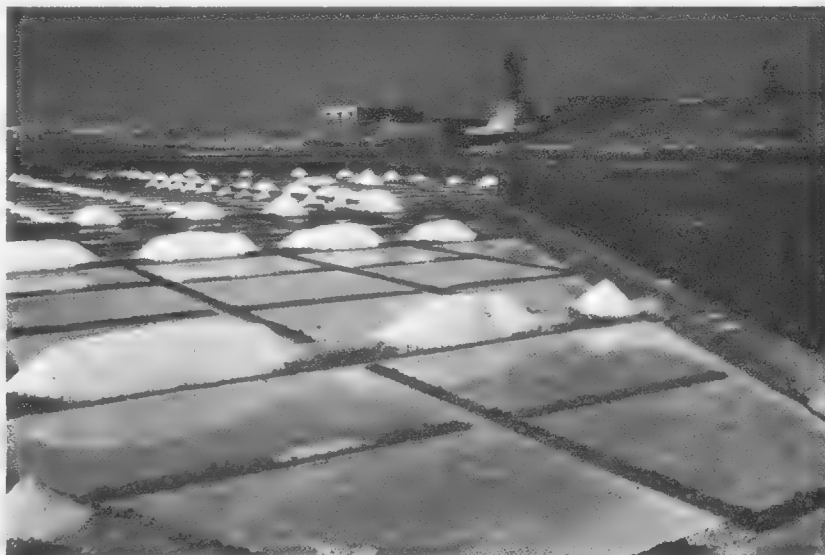
immediately occur and the solution may become supersaturated—stronger than saturated. However, crystallization eventually occurs spontaneously in supersaturated solutions.

Crystallization is important in purifying substances for use in medicine or chemical analysis. The impure mixture is treated with a hot solvent so that the substance required and any more soluble impurities dissolve; less soluble impurities do not dissolve and are separated from the solution by filtering it. The solution is then cooled so that the pure substance crystallizes from it and the more soluble impurities remain in solution. The crystals are finally washed to remove remaining traces of impurities. Sometimes this procedure may have to be repeated to remove all the impurities, particularly if their solubilities are nearly the same as that of the substance required.

Other Solutions

Liquids and gases may dissolve in liquids to form solutions, and all gases mix so thoroughly that a gas mixture can be thought of as a solution. Some solids can absorb gases or liquids to such an extent that they form solutions, at least at their surfaces, and two solids may mix so thoroughly as to form a solid solution.

Liquids that dissolve in one another—for example, water and alcohol—are said to be *miscible*. Oil and water, which do not form a solution, are *immiscible*; they can be stirred to form a mixture of droplets but soon separate into two layers. The constituents of a liquid-liquid solution may be separated by heating the solution and condensing the vapours produced at different temperatures as the constituents boil. This process is called *distillation*, and it is used to increase the alcoholic strength of spirits such as brandy. It is also used to separate the gases present in liquid air and to refine petroleum. The constituents of a liquid-liquid solution may also be separated by adding to it a solvent that will dissolve one of the constituents but not the other. This process is called *liquid-liquid*



Above: Sea water is a solution of salt. In salt pans, shallow pools of sea water evaporate in the heat of the sun to produce salt crystals on a large scale.

extraction and it is used to purify solvents in industry.

A liquid-liquid solution may solidify to form a solution of one solid in another. Many alloys are solid solutions and possess properties superior to those of their constituent metals.

Unlike solids and liquids, the solubility of most gases decreases with temperature. Oxygen in the air dissolves in sea water and supports marine life, and polar waters teem with life because the cold water contains more oxygen than the warm water of the tropics. Solubility also varies with the pressure of a gas. Carbon dioxide gas dissolves under pressure in lemonade and other fizzy drinks when they are bottled. As the top of the bottle is removed, the pressure on the drink falls and the gas comes out of solution, forming bubbles.



Above: Stalactites form in caves when rainwater percolates through the rock from the ground above. The water contains carbon dioxide dissolved from the air, and this solution dissolves calcium carbonate in the rock. On entering the cave, the calcium carbonate crystallizes from the water, producing stalactites.

The Behaviour of Solutions

Solutions have some unusual features. If a porous membrane separates two solutions of unequal concentration, solvent molecules will pass from the weaker solution through the membrane into the stronger solution, endeavouring to dilute it. This process, which is called *osmosis*, continues until both solutions reach the same strength. Water flows into the roots of plants by osmosis, and the quantity of salt in the body fluids must be exactly right otherwise the cells will swell or shrink as they gain or lose water by osmosis. This is why drinking sea water is harmful.

Solutions have higher boiling points and lower freezing points than pure solvents. Dissolving antifreeze in the water in a car radiator lowers its freezing point and prevents the water freezing in winter.

Heat may be gained or lost as a solution is formed. As salt dissolves in water, it takes up heat and a mixture of salt with ice and water can be used for freezing. Sulphuric acid produces a lot of heat when it dissolves in water. For this reason, acid must always be added to water when diluting acid; if some water is added to acid, the great heat evolved will make the water boil and hot acid may spit into the face.



Above: Smoke is a colloidal suspension of solid particles in air.

Colloids

Non-drip paints are special kinds of colloids known as gels, in which liquids are dispersed in solids. They are weak in structure and liquefy on shaking, but reset to a jelly on standing. They will therefore spread easily but do not drip.



Halfway between mixtures and solutions come *suspensions*, materials in which particles, droplets or bubbles of one substance are dispersed within another substance. If the dispersed substance is composed of particles about a ten-thousandth of a millimetre in size, a *colloid* is formed. The particles are so small that Brownian motion (see page 54) keeps them dispersed and they do not come together and settle in a separate layer. The particles may also absorb ions from the medium in which they are dispersed, and gain like electrical charges that keep them separate from one another.

There are several kinds of colloids depending on the phases of the dispersed substance and the dispersion medium. If a gas is dispersed in a liquid—that is, if the liquid is full of fine bubbles of gas—we have a foam. Similarly, a colloidal dispersion of a liquid in a gas—fine droplets of liquid suspended in a gas—is a fog or mist. The table gives all the different kinds of colloids.

Colloids are formed in several ways. Sometimes it is only necessary to mix the two phases; for example, a jelly (droplets of liquid dispersed within a solid) is simply made by adding gelatine to water and allowing it to set. Special chemicals may have to be

added; an emulsion (liquid-liquid colloid) is often made by shaking up the two liquids with an emulsifying agent. Milk is an emulsion of oil droplets in water, and the protein casein acts as an emulsifying agent and prevents the two phases separating. Chemical reactions often produces colloids and physical methods may also be employed, such as grinding substances to the fine particle size required or spraying liquid into a gas as in aerosol sprays.

Colloids have many uses. Ores may be separated from waste rock by finely grinding the ore and rock and suspending the particles in a colloidal dispersion, and then using certain chemicals to form a froth in which only the ore particles collect. This method is known as *froth flotation*. Thixotropic substances are gels (liquids dispersed in solids) that have a weak structure and liquefy when shaken but reset on standing; they are therefore used as non-drip paints. But many substances are useful because they are colloids and have certain properties as a result. They include soaps, dyes, detergents, jellies, foams, sprays, varnishes and polishes.

Sometimes, it is necessary to separate a colloid into its two phases. Preventing harmful fumes from leaving a factory chimney and polluting the air requires a way of separating colloidal particles of smoke and dangerous chemicals in the fumes. An electrostatic precipitator attached to the chimney has electrically-charged plates that attract the particles as they pass and clean up the fumes. A similar process happens where a delta forms as a large river enters the sea. Colloidal particles of clay in the river meet sodium ions in the salt sea water, and the positive charges on the ions neutralize the negative charges on the clay particles. The clay particles no longer repel each other and come together and settle, producing the delta.

A vital process of colloid separation takes place in an artificial kidney machine. Blood is a colloidal dispersion of blood cells and large protein molecules in a solution of salts. When blood reaches the kidneys the solution also contains dissolved wastes such as urea, and the kidneys remove the wastes. A person with kidney disease is progressively poisoned as the kidneys fail to remove wastes from the blood. The kidney machine uses a process called dialysis, by which colloidal dispersions of solids in liquids can be purified. The impure blood is fed from the body into the machine, where it passes over a membrane on the other side of which is a pure solution of the salts in healthy blood. The molecules of wastes pass through the pores of the membrane by osmosis as there are no wastes on the other side, but the protein molecules and blood cells are too large to follow them. The waste materials therefore leave the blood, which is returned to the body in a pure state. Kidney machines can also be used to remove drugs from the bloodstream when people have taken overdoses of drugs.

KINDS OF COLLOIDS

Dispersed Phase	Dispersion Medium	Name of Colloid	Example
Solid	Solid	Solid sol	Coloured glass
Liquid	Solid	Gel	Jelly
Gas	Solid	Solid foam	Pumice
Solid	Liquid	Sol	Soap solution, blood
Liquid	Liquid	Emulsion	Milk, emulsion paint
Gas	Liquid	Foam	Whipped cream
Solid	Gas	Aerosol	Smoke
Liquid	Gas	Aerosol	Fog, mist, spray
Gas	Gas	Colloid not formed	

Energy, Time and Motion

Energy comes in many forms for us to put to use in all kinds of ways. Motion is one product of energy, and motion and time are closely linked. Here motion is achieved by converting potential energy into kinetic energy as the car responds to gravity and hurtles down the slope.



VICKERS VC.10

Energy

Energy is a word of which we hear a great deal nowadays; advertisements for certain foods assure us that they are brimful of energy and yet there is said to be an energy crisis. The word energy is used in so many different ways that it might appear to have several meanings. Although there are in fact several different forms of energy, energy itself can be simply defined in a few words: basically, it is the capacity to do work.

Anything that is doing work—for example, moving another object, heating it or pushing electric current through it—is using up energy in doing so. Therefore anything that is ready to do work—an engine about to pull a train, a pile of sticks ready for lighting, or a battery fully charged with electricity—possesses energy. When work has been done, it will have less energy. The object on which work is done—the train that begins to move, a poker placed in the fire that begins to glow, and a light bulb connected to the battery that lights—all these objects gain energy.

The Forms of Energy

Although one object loses energy as another gains it, energy is not created nor destroyed. The total amount of energy remains the same; it simply changes in form. There are many different kinds of energy, but they can be grouped into a few basic forms.

Potential energy is energy that an object has because of its position. A raised hammer, a wound-up spring and a drawn archer's bow all possess potential energy. This energy is ready to be changed into other forms of energy and do work. When the hammer falls, it will drive in a nail; the spring, when released, will drive the hands of a clock and the bow will fire an arrow. As soon as any movement occurs, the potential energy decreases as it changes into energy of motion (*kinetic energy*). Raising the hammer, winding up the spring and drawing the bow again uses up kinetic



James Prescott Joule

ENERGY, WORK AND POWER

Energy and work are basically similar, work being the expenditure of energy. They are therefore both measured in the same units, the SI unit being the joule, which is named after James Prescott Joule (1818-89), the British physicist who helped to show that different forms of energy can be converted into each other without loss or gain of energy. Power is the rate of doing work or expending energy. An energy source which can do more work in a given time — make anything move faster or heat it more rapidly, for example — is more powerful than another energy source. The SI unit of power is the watt, named after James Watt (1736-1819), the British engineer who invented the first practical steam engine. One watt of power is produced as one joule of work is done in one second; a thousand watt (1 kilowatt) electric fire therefore uses up a thousand joules of energy every second.



James Watt

energy and produces a gain in potential energy. In general, the higher and heavier an object is, the more potential energy it has. One of the most useful sources of potential energy is the water stored behind a dam; this water can pass through pipes and drive turbines as it falls to a lower level, changing some of the potential energy via kinetic energy into hydroelectric power.

Kinetic energy is possessed by anything that is moving, and the faster an object moves, the more kinetic energy it has. Also, the heavier an object is, the greater its kinetic energy (but only when it is moving). Mechanical machines—cars, lathes, pile-drivers or any other machines that use a motor or an engine—produce kinetic energy, and this kind of energy is often called mechanical energy. Vibrating objects possess kinetic energy, and sound, which is a wave of vibrations in the air or any other substance, is a form of kinetic energy. So too is heat, because the heat in an object lies in the motion of its molecules or atoms—the hotter an object is, the faster its molecules or atoms move. However, this kind of kinetic energy is usually called *heat energy* or *thermal energy*.

Electrical energy is energy that is given to an object by passing an electric current through it or giving it an electric charge. It is converted into mechanical energy in an electric motor or heat energy in an electric fire.

Chemical energy is energy that lies in the arrangements of atoms within molecules; by rearranging the atoms, chemical reactions occur and energy may be produced or taken up. Chemical reactions usually produce heat; a burning fire is an example. Chemical energy may also be changed to electricity in a battery and to kinetic energy in muscles.

Radiant energy is energy that can cross space. It includes light, radio waves and heat rays. Radiant heat is not the same as the kind of kinetic energy called thermal energy, but when heat rays strike an object they cause its molecules to move faster and it then gains thermal energy. Light and heat rays are produced by making objects so hot that they glow, as in the filament of a light bulb.

Nuclear energy is energy produced by changing atoms within a substance; it mostly appears as heat, either under control in a nuclear reactor or in an explosion in a nuclear weapon. The Sun produces its heat and light by nuclear reactions. Hence all life on Earth depends on nuclear energy and yet, in the threat of nuclear weapons, is endangered by nuclear energy too.

The Conversion and Conservation of Energy

Each form of energy may be changed into almost every other form in some way, although a series of conversions tends to end in radiant heat or light that escapes into space. If this were not so, the heat from the Sun would make the Earth grow hotter and hotter, and our planet would long ago have burnt up.

ENERGY FORMULAE

Potential energy of a raised object is mgh

where m = mass of the object
 g = acceleration due to gravity
 h = height object is raised

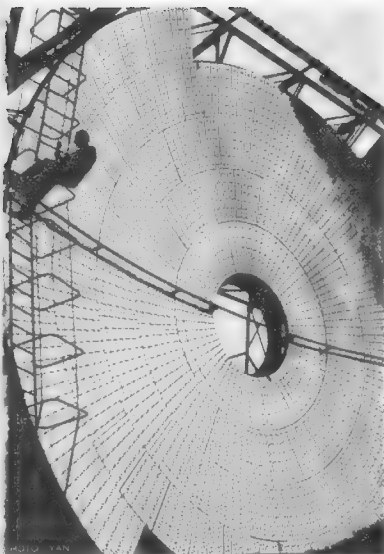
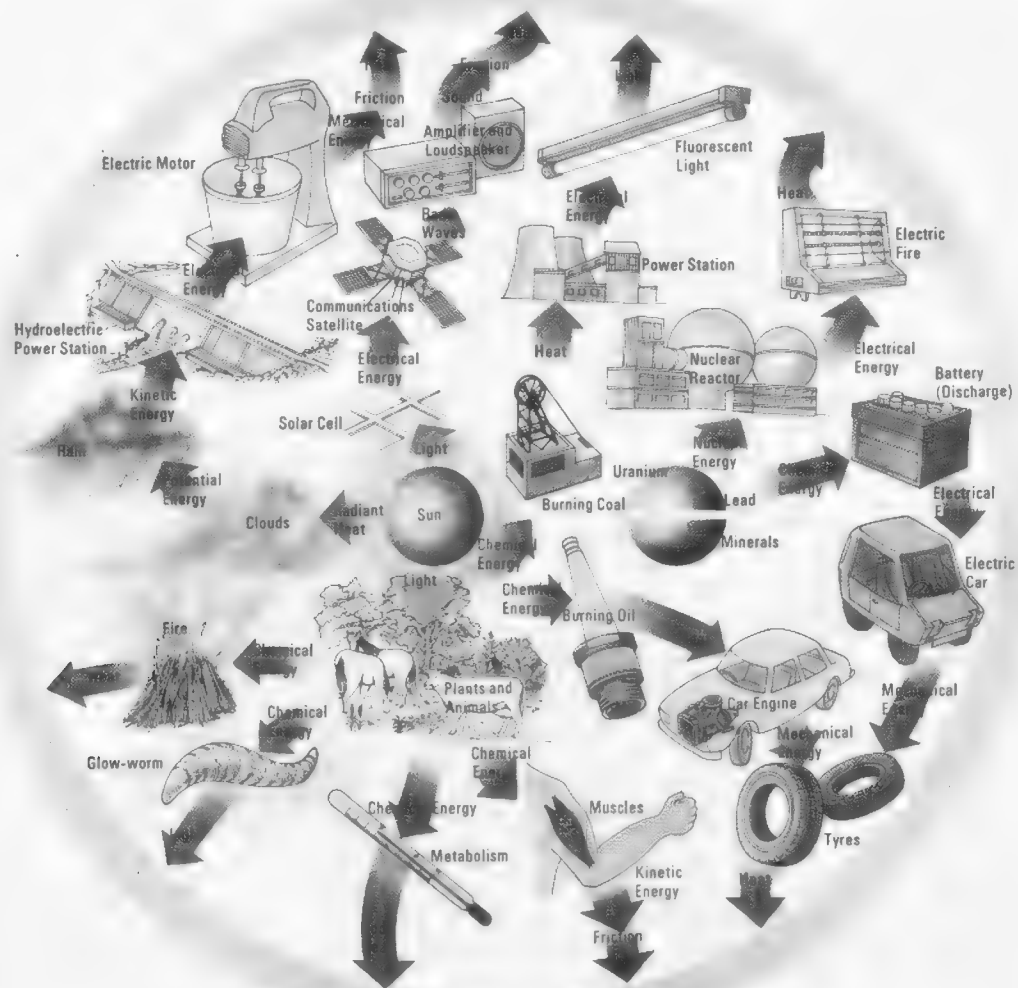
Kinetic energy of a moving object is $\frac{1}{2}mv^2$

where m = mass of object
 v = velocity of object

Electric energy of a current is IVt

where I = current in amperes
 V = potential difference in volts
 t = time in seconds for which the current flows

Right: All the energy that is used on Earth comes from the Sun or from the atom. Every time it is used, energy is converted from one form to another, but the conversions eventually lead to radiation — mostly heat and light — that is radiated away into space



Above: The huge mirror of a solar furnace under construction. Like a magnifying glass, the mirror focuses the Sun's rays at a point and produces a very high temperature. The furnace gives a very clean source of intense heat for scientific research.

Below: Solar energy can be used to heat buildings. This school receives the Sun's heat through the windows and through the roof panels, even in the duller weather.



Somehow, the heat received finds its way back into space. The Earth possesses a vast but fixed amount of energy that is always changing its form; this is in accordance with the principle of conservation of energy—that energy may never be created nor destroyed but may only change its form. In fact, this principle is not strictly true of nuclear reactions, for these create energy from mass (see page 80). However, the amount of nuclear energy created on Earth is very small compared with the other forms of energy.

To illustrate the many changes of energy involved in even a simple action, let us look at the way a motorcar moves. It starts at the turn of a key; here, chemical energy in the body (gained by eating food raised in sun-

light) is changed into kinetic energy in the muscles of the fingers. The key turns a switch that passes electricity from the battery—produced by converting chemical energy to electrical energy—to the starting motor, in which electrical energy is changed into mechanical energy. The motor turns the engine and the generator, in which the mechanical energy is changed back into electrical energy so that a current goes to the spark plugs. There the current is changed into heat as the spark occurs, igniting the fuel in the cylinders of the engine. The fuel burns and produces expanding gases, changing heat energy into mechanical energy, that drive the pistons and, through the gears, start the car moving. The overall energy change is from the chemical energy used up as the fuel burns via heat energy to kinetic energy produced as the car moves. This kinetic energy is mainly converted into heat through friction between the tyres and the road; if you touch the tyres of a car after a long journey, you will find that they have become very hot. This heat radiates away from the tyres, and waste heat also radiates from the engine.

The Energy Crisis

Man consumes an immense amount of energy in running his machines and warming his homes. Most of this energy comes from



A space rocket possesses an immense amount of energy that is ready for use as it stands on the launching pad (top). This energy is in the form of the chemical energy of the fuel inside the rocket. When the fuel burns, the chemical energy is turned into heat, a form of kinetic energy. The heat produces hot exhaust gases that drive the rocket upwards (bottom).

burning fuels such as coal, natural gas and oil that were formed millions of years ago from the remains of plants and animals; for this reason, these fuels are known as fossil fuels.

Fossil fuels are burnt to power engines, produce heat for warming factories, offices and homes, and to produce electricity. They are also used to produce chemicals, particularly plastics. But supplies of fossil fuels cannot last for ever, and unless new sources of energy are found the whole world will be suffering from an energy shortage before long.

Nuclear power is a relatively new source of heat and electricity. It depends on uranium, supplies of which will not last for ever. Controlled nuclear fusion, a kind of nuclear power that would use deuterium (an isotope of hydrogen that is abundant in the oceans), is being investigated in several countries, but experiments have not so far proved successful. Nuclear power therefore cannot be relied upon to solve the energy crisis.

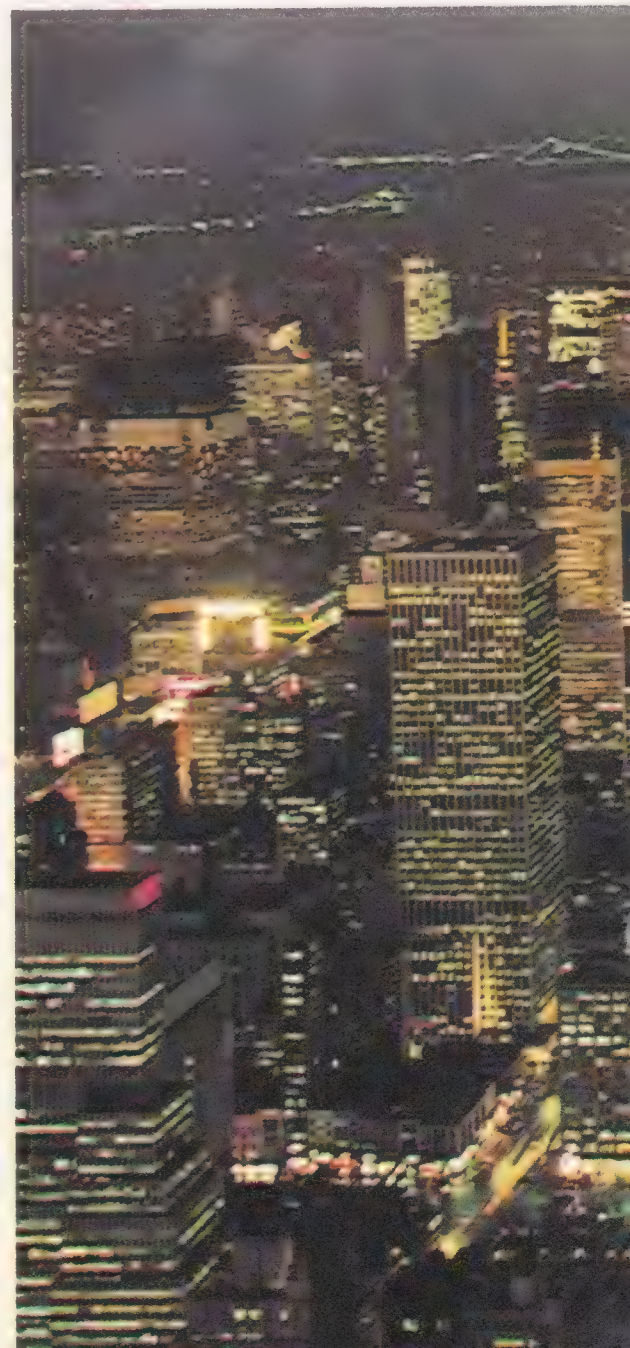
What is required is a source of energy that is always renewing itself. We already have such a source in hydroelectric power, which will be available to us as long as rivers flow down to the sea. However, sources of hydroelectric power are limited and cannot produce all the energy we need. Hydroelectric power is basically a way of tapping the Sun's power, because the Sun's heat causes water to circulate in the atmosphere and fall as rain on high ground and feed rivers.

The Sun's heat is substantial—equal to that of a one-bar electric fire for every square metre of the Earth's surface. Scientists are therefore investigating several ways of using the Sun's heat. Solar cells like those used on spacecraft convert sunlight directly into electrical energy. These are expensive at present, but research is going on to find a cheap method of making them. Possibly, large areas of sunny desert could be covered with arrays of solar cells to provide electricity in bulk. The Sun's heat can also be used directly to provide heat for the home by installing solar collectors on the roof. The main problem with this simple, everlasting and free method of energy production is that the heat is mostly needed at times when the Sun is not shining and little heat is produced, and there is as yet no simple way to store the heat produced when it is shining. A third and futuristic way of taking energy from the Sun that may come about in the next century is to place giant satellites with huge panels of solar cells in orbit above the Earth. These would collect sunlight and turn it into beams of microwaves that would be directed to large aerials on the ground. The aerials would collect the microwaves and turn them directly into electricity. This method could produce large amounts of electricity anywhere in the world. Although expensive to set up, it would then produce energy continually at little extra cost.

Solar power may also be harnessed by using the force of the wind, because winds blow as a result of air movements caused by

the Sun heating the atmosphere. Windmills can produce small amounts of power but a more concentrated energy source lies in the waves of the sea, which are driven by the wind. Just one metre of ocean wave has enough energy to power a hundred homes—if it can all be harnessed. Experiments are taking place to float lines of rocking vanes in the sea; the waves turn the vanes and the resulting kinetic energy is converted to electricity.

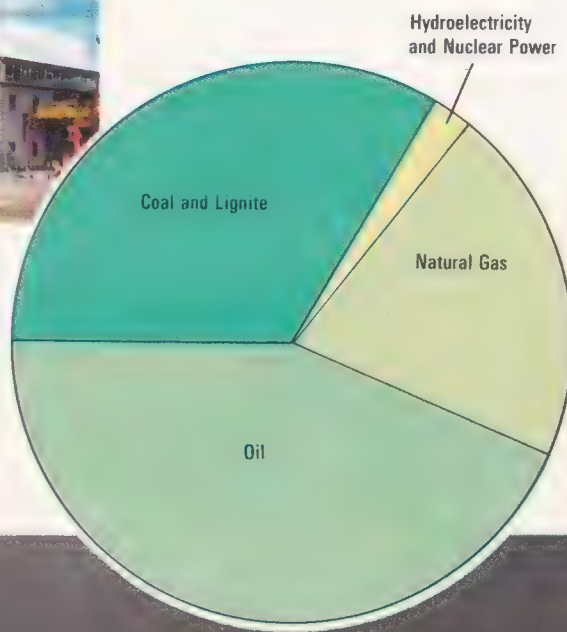
Other new sources of energy originate on Earth. The heat inside the Earth is being tapped by drilling deep boreholes and pumping water down to produce steam. This geothermal power exists naturally in Iceland and New Zealand. The tides also possess enormous energy that can be harnessed by building barrages across estuaries so that the water runs through pipes as the tide rises and falls, turning generators and producing electricity. Places where the shape of the coast allows the construction of tidal power stations are limited, but one exists in France and another is being built in America.



Below: An old steam locomotive changes chemical energy into kinetic energy. The burning of wood or coal in the boiler is a chemical reaction that produces heat, raising steam to power the locomotive.



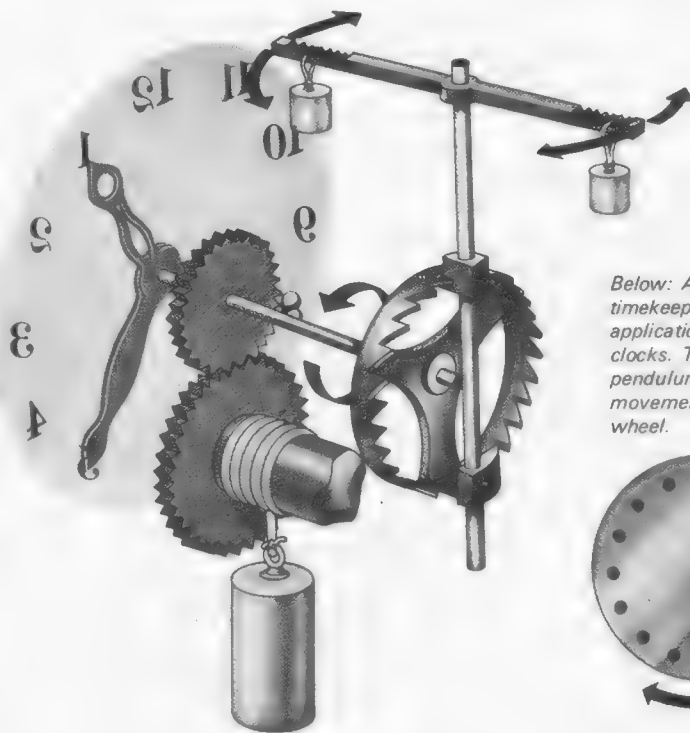
Left: A nuclear reactor produces heat by changing the atoms in its fuel, turning uranium or plutonium into other elements. Engines that utilize chemical energy change the molecules in their fuel and the elements remain unchanged.



Right: The proportions of the different sources of energy that are used to power our world.

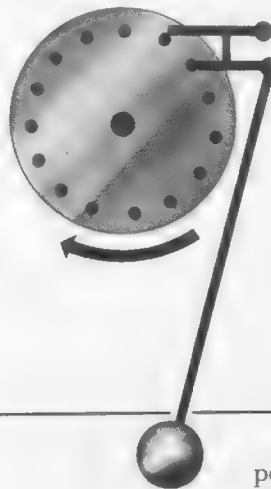
Below: Electrical energy lights New York, keeping the city as alive at night as it is by day.





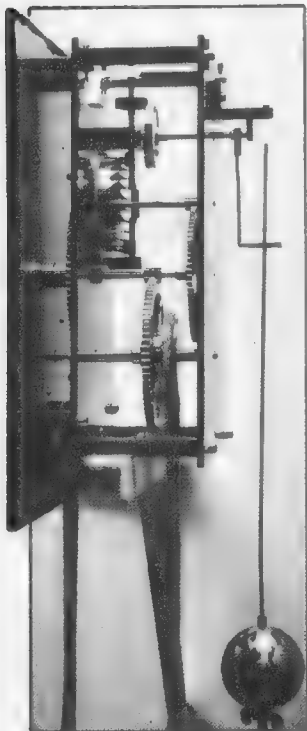
Above: The earliest mechanical clocks were driven by a falling weight and regulated by a rocking bar, or foliot, which allowed a wheel connected to the hands to move round tooth by tooth.

Below: A great improvement in timekeeping came with the application of the pendulum to clocks. The steady swing of the pendulum regulated the movement of pegs attached to a wheel.



Above: Modern pendulum clocks contain a recoil, or anchor escapement. A pair of teeth attached to the pendulum mesh with the wheel and allow it to turn by one tooth at the end of each swing. A spring or falling weight drives the wheel, which kicks the pendulum as it moves and keeps it swinging.

Time



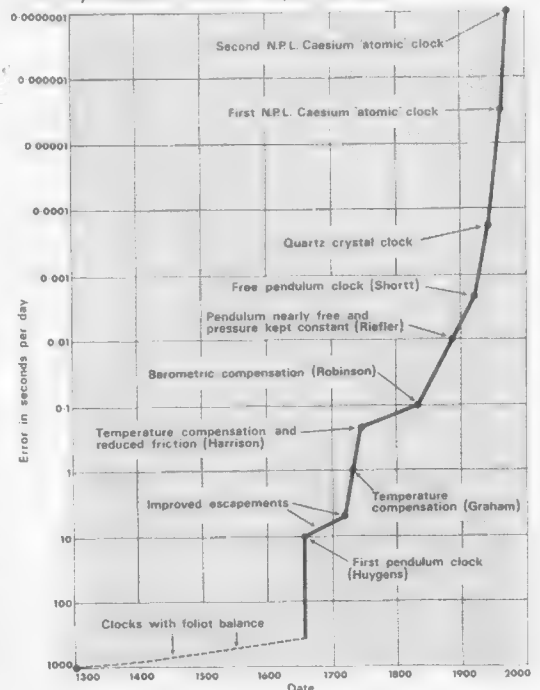
In this pendulum clock, the pendulum turns a small vane to and fro that allows the escape wheel to rotate. This wheel drives gear wheels that drive the hands.

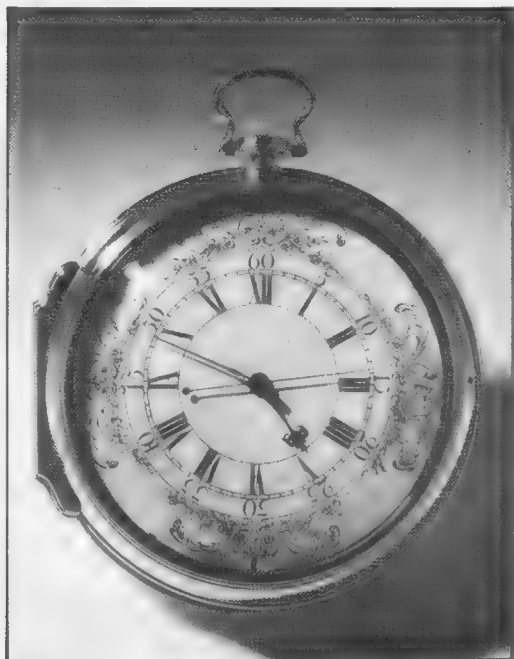
Man must always have been very aware of time—of the passing of night and day and of the changes in the seasons. The Sun and the Moon were worshipped in ancient civilizations and their movements were closely watched. In this way, the first measurements of time were made. A day was simply the time it takes between one sunrise and the next, a month the time it takes for the Moon to go through its phases, and a year the time it takes for the Sun to return to exactly the same position in the sky. To measure smaller intervals of time, the day was later simply divided up into 24 hours each of 60 minutes, each minute consisting of 60 seconds. These intervals have been measured by a variety of devices, from shadow clocks that worked like sundials and could indicate the hour but little more, to modern electronic and atomic clocks that can measure tiny fractions of a second.

Months are now indefinite lengths of time varying from 28 to 31 days, but the day and the year are fixed by the motion of the Earth and cannot be varied. A day is the exact length of time that it takes the Earth to spin once on its axis and a year the time in which it makes exactly one orbit around the Sun. But it turns out that these two intervals of time are not simply related; a year is equal to 365 days 5 hours 48 minutes and 46 seconds (to the nearest second). This gave the ancient

peoples great problems in devising a calendar. The Egyptians believed the year to be exactly 365 days long, but their calendar year was still one quarter-day short. After some time, the seasons began to get noticeably later in the year. Julius Caesar recognized this problem and in 46 BC adopted leap years—having one year of 366 days every four years to gain an average of another 6 hours every year. Even so, the calendar year was now just over 11

The improvement in accuracy of clocks.





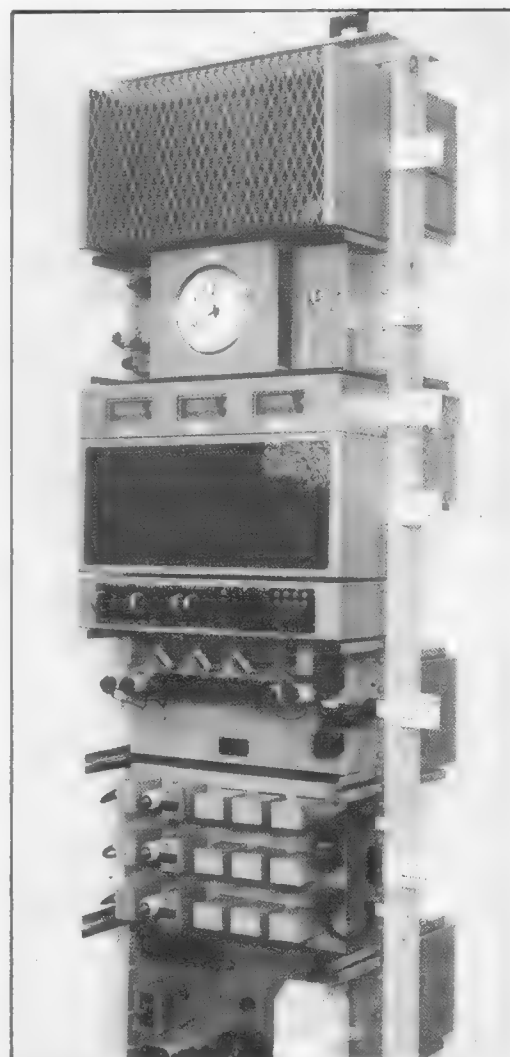
Left: The first chronometers, which are very accurate timekeepers, were made in the 1700s by a British inventor named John Harrison (1693-1776). They were needed to determine longitude at sea, and the British government offered a prize of £20,000 for a good chronometer. Harrison won, although he did not receive the money until shortly before his death. Harrison's chronometer, which was like a large watch, was regulated by a balance spring. He devised ways of keeping its movement constant over a wide range of temperature.

minutes too long and so Pope Gregory XIII reformed the calendar in 1582. We still use the Gregorian calendar, in which every century year (for example, 1800, 1900) is not a leap year except for century years that are divisible by 400 (i.e. 1600, 2000, etc.). This calendar is correct to 26 seconds in a year and can be further modified by decreeing that the years 4000, 8000, etc. will not be leap years, making no further change in leap years necessary for 20,000 years.

A perpetual calendar has been devised in which the year always starts on a Sunday and any particular date always occurs on the same day of the week. Adopting this calendar would save printing new calendars every year. However, there are disadvantages—no one would like their birthday always to fall on a Monday, for example.

Right: The quartz crystal clock keeps time by applying an electric current to a crystal of quartz. The crystal vibrates at a very steady rate and regulates the clock. It has an accuracy of about one second in ten years.

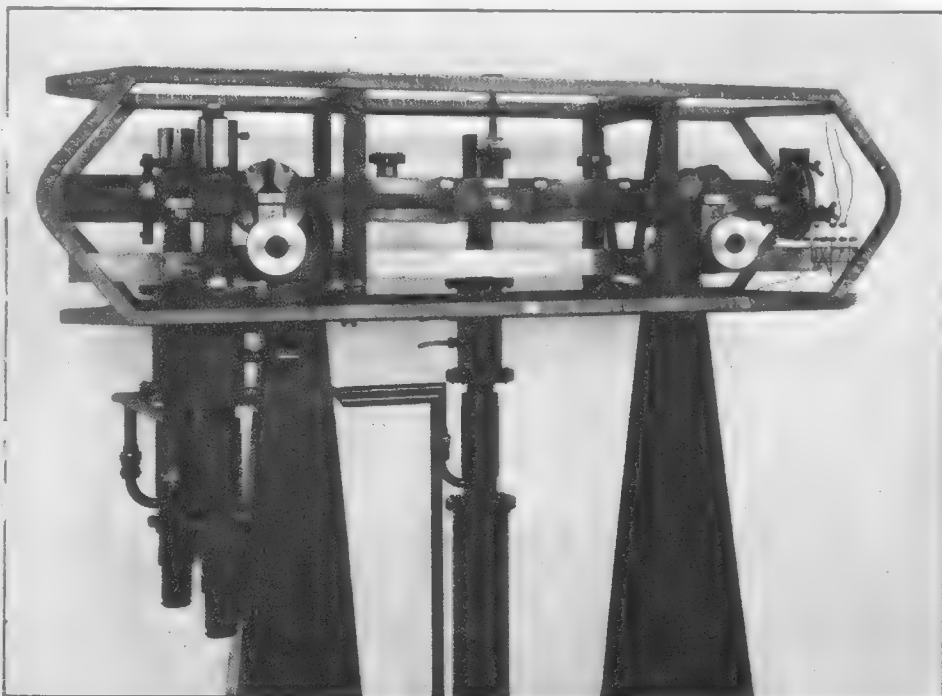
Below: Even greater accuracy can be obtained with an atomic clock, which is regulated by the vibration of atoms. A magnetic field is applied to a vapour, usually of the metal caesium. The resulting vibration of the atoms is so exact that the clock is accurate to one second in 30,000 years. The illustration shows the first caesium atomic clock installed at the National Physical Laboratory (N.P.L.) in Britain.

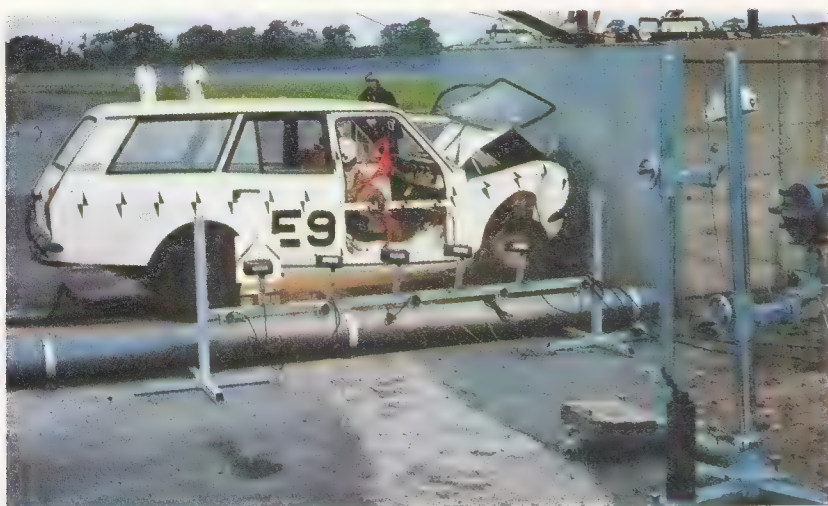


Time and Motion

The ancient Greeks excelled at geometry, which involves measuring lengths precisely, but they had little interest in time and did not invent any method of measuring short intervals of time. To make a clock that can measure time precisely, it is necessary to have a regulator of some kind that produces exact, short intervals of time. But how could such a device be found without a precise clock? The Italian scientist, Galileo (1564-1642) found the answer in the pendulum, which he discovered in 1582. Galileo simply used his pulse to time the swings of a suspended lamp, and found that each swing always takes exactly the same time.

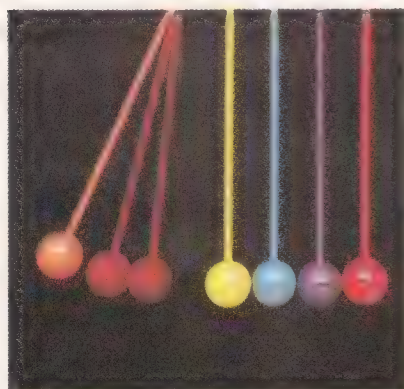
Galileo investigated motion—the change in the distance of an object with time—and his findings on motion led to an understanding of force and ultimately of energy. However, he made those advances without an accurate clock, for the pendulum clock was not developed until after his death. Instead, Galileo probably measured short time intervals with his pulse and possibly also by singing in strict rhythm—for almost everyone has a very good sense of time. He may also have used a kind of water clock in which water flowed from one vessel into another for the time being measured, the weight of the water indicating the time interval.





Once set in motion, any object continues to move unless it is acted upon by a force. In a car, the occupants will carry on moving if the car stops suddenly. Unless they are securely fixed to their seats, they will fly forward and strike the windscreen if the car should crash. Here a car crash is simulated with dummy occupants to find out what dangers the driver and passengers would face in a real crash.

In a collision, one object imparts a velocity to another as momentum (mass \times velocity) is transferred from one to the other. Momentum may also be carried through a line of objects in contact with each other. Here, the two red balls at each end of the line of five swing alternately to and fro. As one strikes the end of the line, its momentum is transferred down the line to the final ball, which is knocked away as if the first ball had struck it directly.



Why does an arrow fired from a bow continue to move through the air after it has left the bow? This question perplexed people long ago, and it is easy to see why. At that time, things were made to move only if a man or a horse or ox pushed or pulled them—yet the arrow flew through the air without any aid at all. Another fundamental question about motion could also have occurred to them: why do things fall to the ground? Eventually one man answered both questions and although they may both seem simple, it took one of the greatest scientists the world has seen to solve them. This man was Sir Isaac Newton, the British physicist and mathematician who lived from 1642 to 1727.

Newton discovered the three basic laws of motion that now bear his name. The first law answers the question about the flight of an arrow and states that **an object will remain at rest or will continue to move at the same speed in a straight line unless it is acted upon by a force.** That is, once an object such as the arrow has begun to move, it will keep on moving constantly until something either stops it or changes its motion in some way. No action of any kind is needed to keep it moving. This is why the planets always continue to move through space. They began to move when the solar system

THE EQUATIONS OF MOTION

Three equations explain the motion of any object that is accelerating at the same rate. They are

$$v = u + at$$

$$s = ut + \frac{1}{2}at^2$$

$$v^2 = u^2 + 2as$$

where a = acceleration
 t = time for which acceleration takes place
 u = velocity at start of acceleration
 v = velocity at end of acceleration
 s = distance travelled during acceleration.

In the case of a falling body, a is the acceleration due to gravity (g), which is equal to 9.8 metres/sec/sec.

was formed, and it is not that there must be something in space to keep them moving but simply that there is nothing in space to stop them moving.

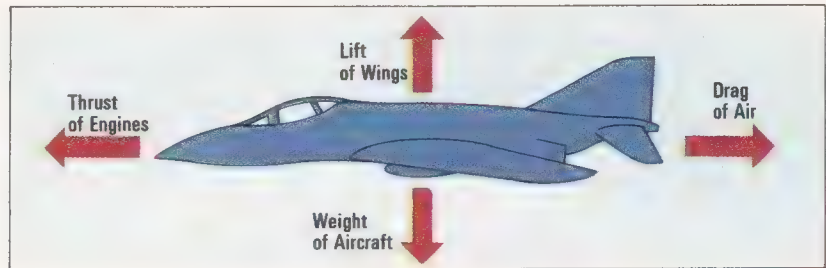
A force is therefore a kind of push that acts to begin motion or change motion. When a force acts, it uses energy and produces work. There are several kinds of force, just as there are several forms of energy. The expansion of anything when it is heated produces a force as its size increases; the power of the motor car, aircraft and rocket comes from the force of expansion of hot gases. The force produced by muscles comes from chemical changes in the muscles that make the muscle fibres contract. Electrical fields and magnetic fields both produce force.

Gravity is another kind of force that Newton himself discovered, simply by asking himself the second of our basic questions on motion—why do things fall to the ground? Galileo had found that objects accelerate as they fall; that is, their motion is changing. Newton realized that a force must therefore be acting on a falling body and this force is the pull of gravity. He said the answer came to him when he saw an apple fall from a tree, and the SI unit of force, which is called the *newton* after him, is by coincidence approximately equal to the weight of an apple. The pull of gravity exerts a force on everything at the surface of the Earth, and this force is the weight of anything.

Friction

Another important kind of force acts only when objects are in motion, and it always acts to slow their motion. This force is called *friction*, and it is caused by contact with the medium in which an object is moving or with the surface on which it is moving. The friction produced in a medium is its viscosity (see page 60). Friction with a surface depends on the pressure between the object and the surface;

Perpetual motion machines have fascinated people for centuries. In this design, water is raised by the screw, which is turned by the same water falling in a cascade and striking blades attached to the screw. However, the motion stops because work has to be done to overcome friction and, after starting it, no energy is put into the machine to do work.



Above: Four main forces act on an aircraft as it flies through the air. The aircraft flies at constant speed if the thrust equals the drag, and at the same level if lift equals weight.

Below: A scientist examines how a tyre displaces water. In wet weather, rainwater must flow away along the treads so that it cannot come between the tyre and the road surface and destroy friction.

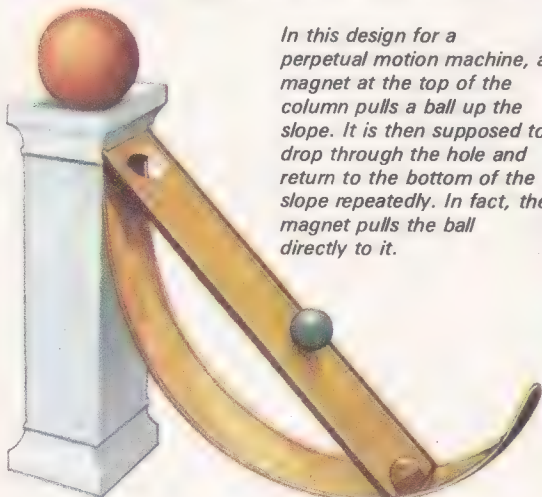
the greater this pressure, the greater the friction. This can be easily demonstrated by sliding your finger along a smooth tabletop; if you press hard, friction increases and your finger comes to a stop.

Although it opposes motion, all forms of transport that run on wheels could not move without friction. Friction between the wheel and the ground enables the wheel to grip the ground and produce movement; if there were no friction, the wheel would simply slide and spin (which happens when friction is reduced on ice or in mud).

It might seem odd to say that no force is needed to keep something moving when a jet aircraft flies at a constant speed using its powerful engines. The reason is that the force of the engines pushing the aircraft forward is equalled by the friction with the air through which the plane is moving; the two forces balance each other so that no overall force is acting on the aircraft and it therefore continues to move at a constant speed. Increase the power of the engines and the aircraft will move faster until friction increases to match the increased force; it will then be moving at a higher but constant speed



In this design for a perpetual motion machine, a magnet at the top of the column pulls a ball up the slope. It is then supposed to drop through the hole and return to the bottom of the slope repeatedly. In fact, the magnet pulls the ball directly to it.



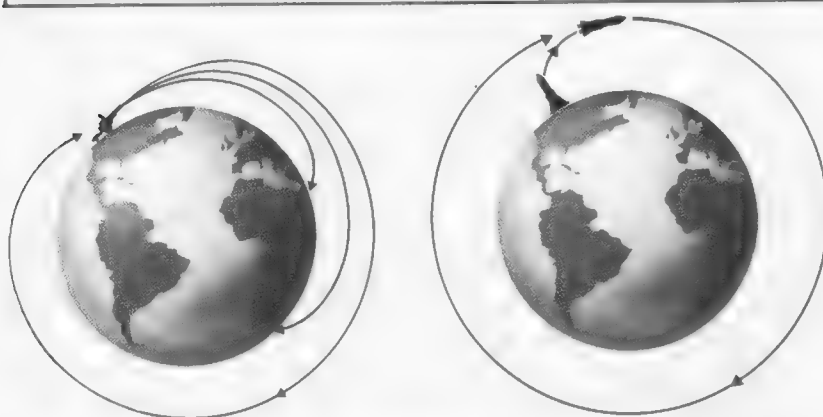
MASS, WEIGHT AND INERTIA

The Apollo astronauts were weightless on their journeys to the Moon and had only a sixth of their normal weight while they stayed on the Moon. However, at no time did their *mass* change.

At a given point, the ratio of the masses of two bodies is directly proportional to the ratio of their weights (i.e. to the forces which they exert on what ever is supporting them). The actual weight of a body, however, depends not only on its position in space but also on its motion. Thus a man in space may have no weight because of his motion, although gravity still pulls him towards the Earth. A man on the moon will only weigh one-sixth of his weight on Earth, due to the smaller pull of the moon.

Inertia is the tendency of anything to

resist a change in its motion and it is related to mass. Inertia has to be overcome to get an object moving and, once moving, it has to be overcome again to stop it moving. A massive object has great inertia, as you will know if you have ever pushed a motor-car. The astronauts were able to lope about on the Moon because their weight was low—that is, gravity did not pull them to the ground as strongly as on Earth. But inertia did not change because mass did not change. If the astronauts' moon-car had broken down, they would have had little trouble in lifting it as its weight would have been low. But they would have found that just as much effort would have been needed to push it back to the lunar module as would have been required on Earth.



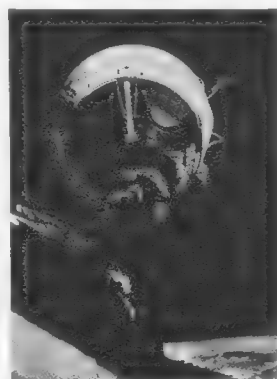
The resulting acceleration or retardation will depend on the size of the force and on the mass of the object. A greater force will produce a more rapid change in velocity but a greater mass will undergo a less rapid change. This is expressed in Newton's second law of motion, which can be stated as force is equal to mass multiplied by acceleration (or retardation). However, Newton preferred to use the quantity known as *momentum*, which is equal to the velocity of a moving object multiplied by its mass. The second law then states that **the rate of change of momentum is equal to the applied force.**

You are most likely to be reading this while sitting on a chair. The Earth's gravity is producing a force on you that is acting to pull you down. Yet you do not move. Another force must be acting to oppose gravity, otherwise you would move. This force is an upward force in the legs of the chair, and it is called the reaction to the action of gravity. Newton's third law of motion deals with this situation and states that **action and reaction are equal and opposite.** Whenever any force acts, an equal force also acts in the opposite direction. Note that action and reaction occur only when one object exerts a force on another.

Let us look at the momentum of two colliding objects. Because action equals reaction, they exert the same force upon one another as they part and, by Newton's second law, the same rate of change of

Above: Imagine a shell being fired from a more and more powerful gun (left). It would fall farther and farther away until, in theory, it would fall around the Earth and return to the gun. In fact, friction with the air would cause the shell to burn up. However, this is basically how a spacecraft orbits the Earth (right). It is launched into space with sufficient speed to send it on a path around the world. No air exists in space to slow the spacecraft, and once in orbit, it continues to travel around the Earth.

Below: A two-man Gemini spacecraft in Earth orbit.



momentum occurs. Because the forces act for the same length of time—the time the two objects are in contact—the same change in momentum occurs to each object. One object will lose momentum of a certain amount and the other will gain the same amount. But overall, there is no change in momentum. This is the principle of *conservation of momentum*; in any system, the total momentum never changes. In a game of snooker, the balls are continually colliding. As one ball meets another, it imparts a certain velocity to it and the first ball loses velocity; in each collision and over the table as a whole, momentum is conserved.

Because momentum is mass times velocity and the balls have the same mass, they impart similar velocities to each other. But if a light object collides with a heavy object, the resulting velocities are different. When a peal is rung on a church bell, the clapper strikes the bell again and again at high speed but the bell, being much heavier, just swings gently to and fro as it rings.

When a force acts and motion results, work is done. The amount of work done is equal to the force multiplied by the distance through which it acts. The SI unit of work is the joule, and one joule is equal to the work done when a force of one newton moves through a distance of one metre in its own direction.

Adding Forces

Newton's law of motion and the equations of motion show how an object moves in a straight line; we have considered velocity and acceleration but not *direction*. When one force acts on a body, it will move in the direction taken by the force. But if two or more forces act at the same time, they may each act to push the object in different directions and the direction it finally takes will depend on the size of the forces involved and the direction in which each one acts.

If you try to row a boat across a fast-flowing river, you soon find that you cannot steer directly towards the point at which you wish to land because the current sweeps you downstream. You have to face upstream at a certain angle so that part of your motion opposes the flow of the current while the other part takes you across the river. Aircraft navigators have to allow for winds blowing them off course in exactly the same way.

If two forces are added together but at least one of them is producing an acceleration, then the resulting motion will be a curve. This can easily be seen by throwing a stone into the air. The motion can be resolved or separated into two components at right angles, one horizontal and one vertical. The horizontal component keeps the stone moving forward at a constant rate (neglecting friction with the air), but the vertical component is affected by gravity. In a vertical direction, the stone rises and slows to a stop and then falls with increasing speed until it hits the

ground. Combining these components, the stone's final motion is a curve called a *parabola*, and it hits the ground some distance away. Its range depends on the angle at which it is thrown as well as its speed. Archers and gunners can make precise estimates of the paths of projectiles—in their case, arrows or shells.

Any object that is moving in a circle—a satellite, a car going round a corner, a stone being whirled around on a piece of string—is constantly changing direction and is constantly being accelerated in any one particular direction; it is therefore always subject to a force. The force is directed towards the centre of the circle and it is called *centripetal force*. In the case of a satellite, the centripetal force is the Earth's gravity pulling it into an orbit; with the car, it is the friction of the tyres with the road steering it into a circle, and with the stone, the centripetal force is the tension in the string. All act to prevent the object from leaving its circular motion. The Earth cannot lose its gravity but the car may leave the road and the stone's string may break, in which case they move forward in the direction they are travelling at the instant this happens. Inside the car, the passengers seem to be pushed to the outside of the car as it corners. The term centrifugal force is sometimes used to describe this action, but this kind of force does not actually exist. All that happens is that the passengers tend to move straight ahead as the car corners, and the car moves towards them as it begins to change direction.



At any instant, a rider and chairplane seat, considered as one body, are subjected to two external forces. One is the force of gravity pulling them towards the centre of the earth and the other is the tension in the supporting cable. This latter force can be divided into two components, one acting vertically upwards and the other acting horizontally towards the axis about which the rider and seat are rotating. The vertical component balances the downward pull of gravity so that the rider remains suspended in the air, remaining in the same position relative to the support. The horizontal component provides the force necessary to produce circular motion.

Rotation

An object spins when it is given a particular combination of forces called a *couple*, which consists of a pair of forces in opposite directions applied to opposite sides of the object. Spinning a coin demonstrates how a couple is applied. Rotating objects possess some unusual properties, for example a kind of momentum called *angular momentum*. This is related to the mass, size and spin of the rotating object: the greater its mass, the larger its diameter, and the faster its speed of rotation, the greater its angular momentum. Angular momentum remains constant in a spinning body if no force acts to speed it up or slow it down. This means that if a rotating body changes its diameter, then its speed of rotation must also change so as to conserve angular momentum. This can be seen when spinning ice-skaters suddenly draw in their arms. They immediately spin faster because they are reducing their diameter.

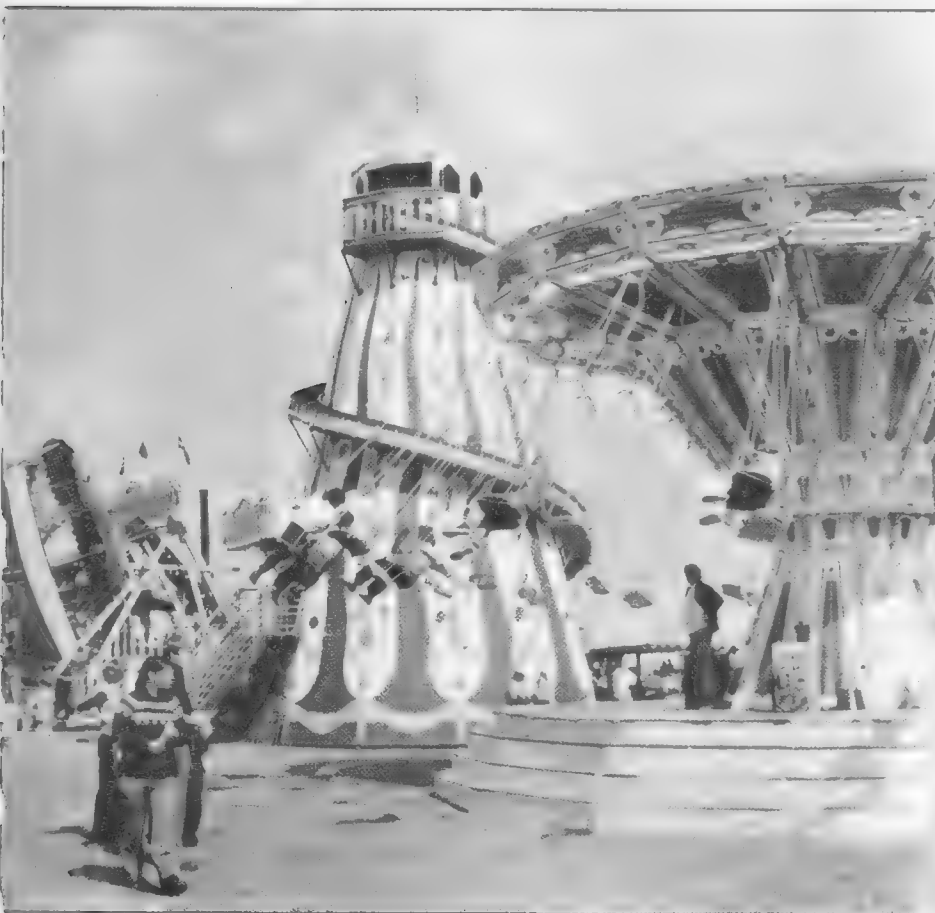
The gyroscope is a particular kind of rotating body. It is simply a spinning disc mounted in a frame, rather like a bicycle wheel. Conservation of angular momentum ensures that the axle of the gyroscope does not change its direction once it has been set spinning. The gyroscope can therefore be used as a compass. A gyrocompass indicates the direction in which a ship or aircraft is heading much more accurately than a magnetic compass, and it also acts as a controller for automatic navigation devices.

Another characteristic of spinning bodies, and one particularly exhibited by the gyroscope, is precession. If the axle of the gyroscope is forcibly turned, then it will move in a direction at right angles to the direction in which the turning force is applied. If a toy gyroscope is set spinning and one end is placed on a pivot, then the gyroscope will begin to keel over as the force of gravity acts vertically on the axle. However, precession ensures that a movement at right angles to the vertical force takes place and the whole gyroscope begins to move in a horizontal circle around the pivot. This effect can be felt if you have ever set a bicycle wheel spinning rapidly, grasped it by the axle, and tried to turn the wheel; precession will make the wheel twist almost out of your hands.

Equilibrium

Objects or structures that are not moving are still subject to forces. The weight of every part of a structure imposes a force on the neighbouring parts of the structure, and if the structure is to stand, then all the forces in all the parts of it must balance each other so that there is no overall force acting on it. The branch of mathematics that is concerned with forces in balance or in equilibrium is called *statics*, whereas forces causing motion are studied in *dynamics*.

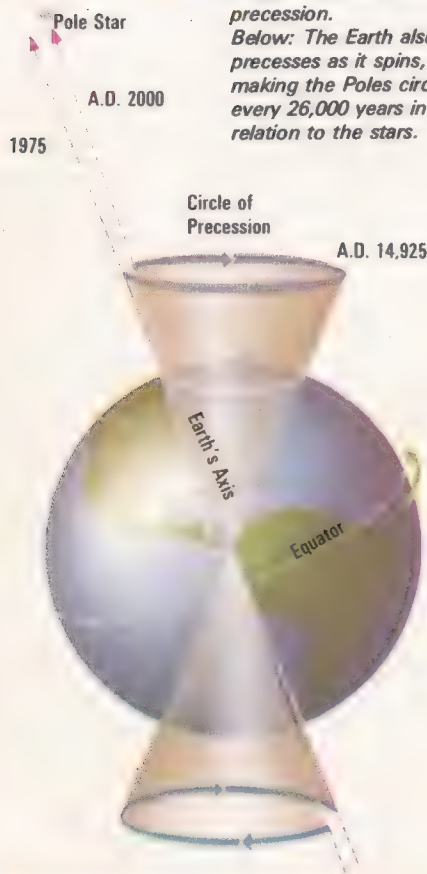
The various sections of buildings and structures such as bridges must be carefully





Above: A gyroscope circles around its pivot because of precession.

Below: The Earth also precesses as it spins, making the Poles circle once every 26,000 years in relation to the stars.



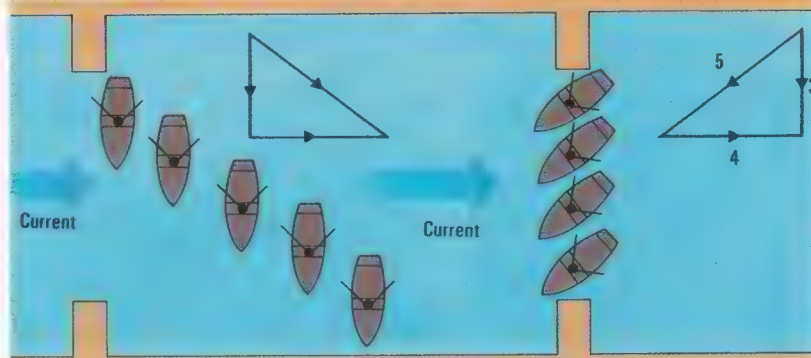
THE PENDULUM

A pendulum swings to and fro at a constant rate, every swing taking exactly the same time, provided the swings are not too large. It would continue to swing for ever if friction did not eventually bring it to a halt. The pendulum is therefore a good device for regulating clocks and has been used for this purpose for three centuries. The period of the swing of a pendulum depends on its length but not its mass, and the time-keeping of a pendulum clock is adjusted simply by raising or lowering the weight at the end. The period also depends on the force of gravity, and a pendulum can be used to make an accurate determination of gravity.

VECTORS AND SCALARS

A *vector* is any quantity that has both size or magnitude and direction. Velocity and force are both vectors. Speed, however, does not have direction but only magnitude; it is therefore a *scalar* quantity. For example, a car can travel along a winding road at a constant speed but its velocity will change because it is always changing direction. A boat heading due north at 30 km/hr

has a velocity to the north of 30 km/hr, but its velocity to east or west is zero because it is not moving in these directions. Its speed is simply 30 km/hr. Vector quantities can be represented by drawing lines; the length of the line represents magnitude and the angle direction. The effects of adding forces may be calculated by drawing vector diagrams in this way.



Above left: A boat heads across a river at 3 km per hour but is swept to one side by the current flowing at 4 km per hour. Its final velocity can be found by constructing a vector diagram in the form of a triangle in which two sides represent the speed and direction of the boat and current and the third side represents the final velocity, which is in a diagonal direction at 5 km per hour.

Above right: The boat can move straight across if it heads into the current at 5 km per hour. The vector diagram shows that it will then be carried straight across the river at 3 km per hour.

Below: An astronaut floats weightless in space high above the Earth.



WEIGHTLESSNESS

It is often thought that spacemen are weightless because they fly far away from gravity, but this is not true. A spacecraft and all its occupants are always influenced by a field of gravity, whether it is the Earth's, the Moon's or the Sun's gravity. Except when its engines are firing, a space-craft coasts through space completely under the influence of gravity, no matter whether it is orbiting the Earth or flying to the Moon or planets. On Earth, we have weight because gravity pulls us down to the ground. We can stand on some scales and measure the force with which we press on the ground—that

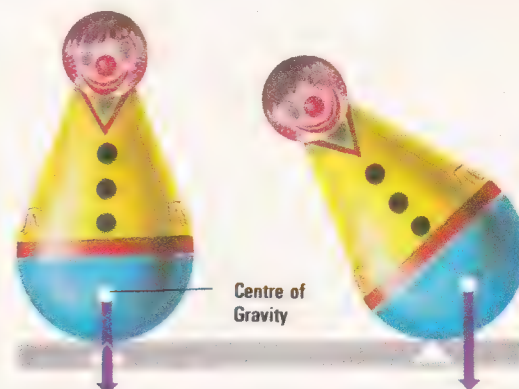
is, we can read our weight. But in space, there is no ground; the space-craft responds to gravity just as much as its occupants do. They cannot press down on the floor of the spacecraft because it is moving in exactly the same way as they themselves are. The spacemen and their craft therefore have no weight and, unless they tether themselves to the floor in some way, float about the cabin.

In the same way, anything falling is responding to gravity and is weightless; sky-divers are an example. For this reason, weightlessness is sometimes also called *free fall*.

designed to produce equilibrium. To take a simple example, consider a ladder leaning against a wall. The weight of the ladder acts downward and reaction to the weight and friction with the wall and ground at each end all balance each other so that the ladder does not move. If a vector diagram is made of such a structure, the lines representing the forces will meet and form a closed pattern. If this were not so, there would be an overall force acting and the ladder would move. In practice, this happens if the ladder is overloaded, and the forces of friction become insufficient to stop the ladder slipping.

In studying objects or structures in equilibrium, it is useful to locate an internal point called the *centre of gravity* or *centre of mass*. This is a point at which the entire mass of the structure or object can be thought of as being located. The centre of gravity of a symmetrical body such as a ball is at its centre, but in odd-shaped objects it may lie near one edge. The location of the centre of gravity is important in determining the stability of an

Right: This toy figure always springs up right no matter how much it is tilted. The centre of gravity is so low that it always remains to one side of the point on which the toy pivots and gravity pulls it back upright.



object, particularly a vehicle such as a car or ship. An object will fall over only when it is tilted so much that its centre of gravity comes above a point outside the base of the object. Objects with a low centre of gravity therefore have good stability. In an object with a heavy base, such as a lamp-stand, the centre of gravity is low and it is difficult to make it fall over. A stool on the other hand has a high centre of gravity and is easily knocked over.

Below: Acrobats perform extraordinary feats of balance, somehow always managing to keep their centre of gravity exactly above their support.

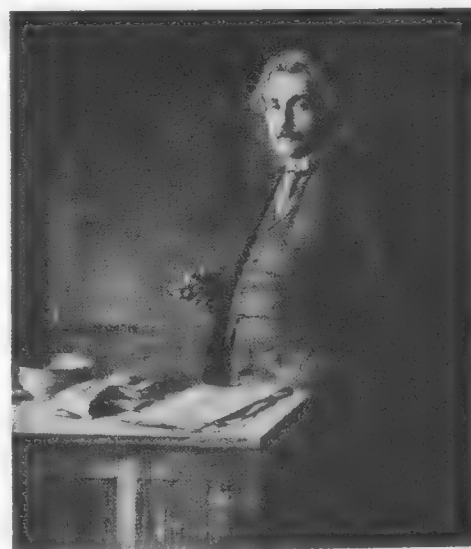
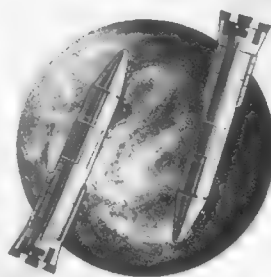


Relativity

Sometimes you can sit in a train at a station and think it has started to move, and then suddenly realize that you are still stationary and another train alongside is leaving in the opposite direction. For a moment, you are not sure whether you are moving or not; all you know is that one train is moving relative to the other. All motion is in fact relative; there is no central stationary point in the Universe against which motion can be measured. Your train may be travelling over the ground, but the ground itself is moving as the Earth circles the Sun. Furthermore, the Sun is moving as the Galaxy spins and the Galaxy itself is also in motion. Everything in the Universe is moving, and consequently motion cannot be measured absolutely; all one can say is that one object is moving at a certain velocity relative to another object.

From this idea, and from the fact that the speed of light is always observed to be the same no matter how fast the observer is moving, Albert Einstein deduced some astonishing conclusions. These were presented in the *Special Theory of Relativity*, which was published in 1905 and revolutionized physics. The main conclusion was that length, mass and time are all affected by motion. If an observer looks at an object or system of objects in relative motion to him, he will observe that length decreases in the direction of motion, mass increases and time slows down the faster the system moves. The effects are too small to be noticed at the speeds we observe on Earth, and Newton's laws of motion still hold

Two spacecraft pass one another, each travelling at 30 km per second as measured from Earth. But each spacecraft will be approaching the other one at 60 km per second. Their velocities are 30 km per second relative to Earth, but 60 km per second relative to each other. However, if observers on both spacecraft and on Earth then measured the velocity of light coming from the Sun, they would all get exactly the same figure — nearly 300,000 km per second. This illustrates the two postulates of the *Special Theory of Relativity*: that all motion is relative and that the velocity of light is always constant, no matter how it is measured.



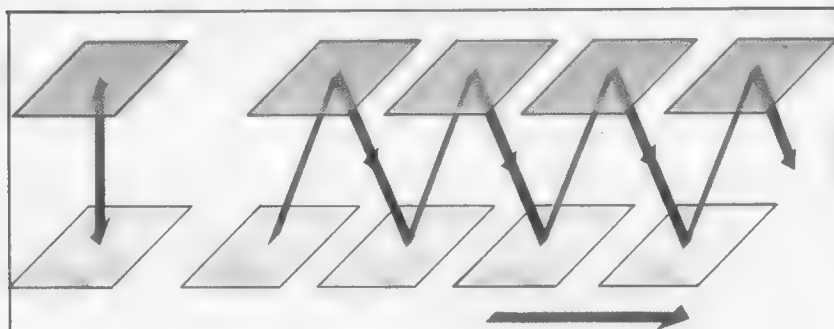
Albert Einstein (1879-1955)

good. But if the relative motion reaches the speed of light (300,000 kilometres a second), then in the observed system, length becomes zero, mass infinite and time slows to a stop. Clearly, such a situation is impossible and so Einstein concluded that relative motion at or beyond the speed of light is impossible; that is, nothing can move faster than light. Time slowing and mass increase have since been observed in atomic particles that move at very high speeds. Length contraction has not been found and it would be difficult to observe, but it must follow from the other effects of relativity.

If an atomic particle is given more energy, it travels faster. As more and more energy is pumped in, it will approach the speed of light. Its mass then increases substantially but its speed does not get much greater. The extra energy mainly produces an increase of mass. Einstein deduced that mass and energy are related to one another by the famous equation $E=mc^2$, in which E is energy, m is mass and c^2 is the speed of light multiplied by itself. As c^2 is such a huge quantity, a little mass is equivalent to a vast amount of energy. This was later shown to be true when nuclear power was released.

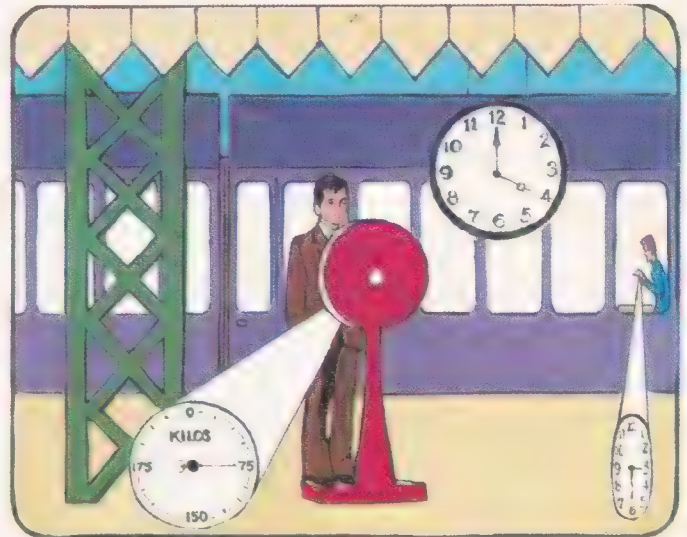
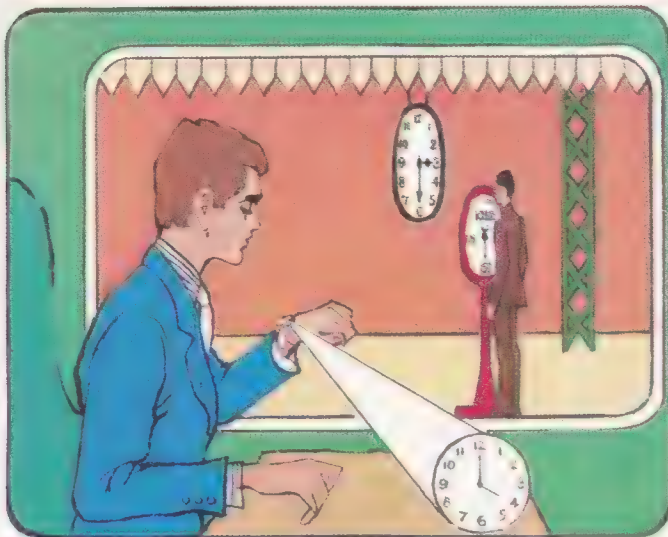
The *Special Theory* considers systems in relative motion at a constant velocity. Einstein went on to consider the effects of acceleration, and published his conclusions as the *General Theory of Relativity* in 1916. The basic ideas behind this theory are that gravity is equivalent to acceleration, and that light bends in an accelerating system.

The first idea will be familiar to anyone who has gone up in a high-speed lift. As the lift suddenly starts to ascend, a feeling of greater weight suddenly occurs. The slight increase in weight is caused by the floor of the lift pushing against the feet as the lift accelerates, but the effect is exactly the same as would be caused by a sudden increase in gravity. In fact, anyone inside the lift (provided they could not see out) could not prove which had occurred—a gravity increase or



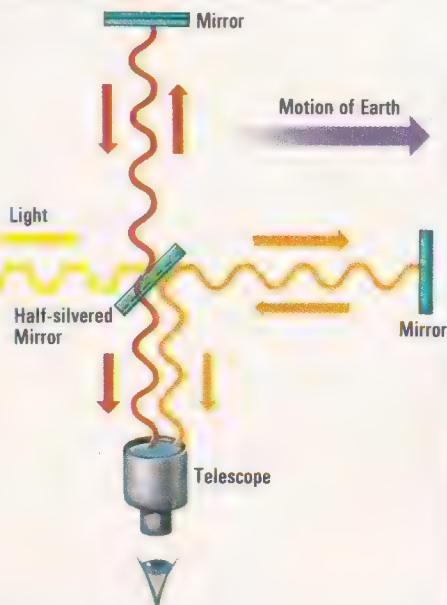
THE LIGHT CLOCK

The fact that time slows with motion can be shown by considering a simple light clock. This clock consists of two parallel mirrors with a pulse of light bouncing to and fro between them; the reflections of the pulse would mark out regular intervals of time (left). If this clock were to move as shown, the pulse would appear to zig-zag between the mirrors and travel a greater distance (right). As light always travels at the same speed, it would take longer for the pulse to get from one mirror to the other. Anyone observing the light clock in motion would see that it is marking time slower and slower as it gets faster. If the clock were to move at the velocity of light, then the pulse would never get to the next mirror; time would have slowed to a stop. But at the clock itself, time would not appear to have changed.



THE MICHELSON-MORLEY EXPERIMENT

This experiment was first performed in 1881 to detect the ether, a medium of unknown form that was thought to pervade the Universe. The ether was believed to carry light waves rather than air carries sound waves. Albert Michelson (1852–1931) and Edward Morley (1838–1923), both American physicists, used an interferometer to detect the ether. A ray from a source of light was divided by a half-silvered mirror into two rays at right angles, each of which went to a mirror. On returning from the mirrors, the two rays were combined by the half-silvered mirror and viewed through a telescope. Fringes were seen because interference occurred between the two rays. The whole interferometer was then turned through a right angle and the fringes viewed again. A change in the pattern of fringes was expected because, if the Earth moved through the ether, each ray would take a different time to travel to and from the mirrors and the rays would change their phase. In fact, no change was seen in the fringes, showing that the rays took exactly the same time to travel their respective paths, regardless of the Earth's motion through space. This result showed that the ether does not exist and that the velocity of light is always the same, regardless of the motion of the observer. Without an ether, there is also no absolute basis on which to measure the motion of any object.



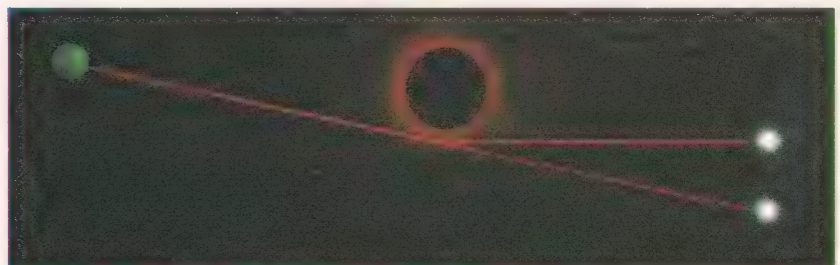
an acceleration. The forces produced by gravity and acceleration are therefore identical. The second basis of the General Theory was proved in 1913 by rotating an interferometer like that used in the Michelson-Morley experiments. As an interferometer rotates—that is, accelerates in any one direction—the path of a light ray in the interferometer curves.

Einstein deduced from this that as light is bent by acceleration, it must also be bent by gravity and he estimated the amount of bending. He was proved triumphantly right during the solar eclipse of 1919, when stars could be seen near the Sun because the Sun's disc was covered by the Moon. These stars seemed to change position, showing that light rays from the stars to the observers on Earth had been bent as they passed through the Sun's gravitational field. And the amount of bending was that predicted by Einstein!

This conclusion can be thought of in a more general way: that gravity distorts space. Light or anything else travelling through space finds its path curved by a gravitational field because distance is shortened by gravity. The effects are noticeable only in a strong field of gravity such as that of the Sun. The General Theory also explained a constant shift in the orbit of the planet Mercury that could not be accounted for by Newton's theory of gravitation. It also predicted that light would get redder in a gravitational field because gravity would slow its vibrations, and this reddening has been observed in the light from stars. Another prediction that follows from the general theory of relativity is that black holes may exist in space.

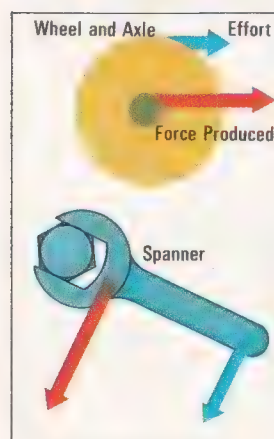
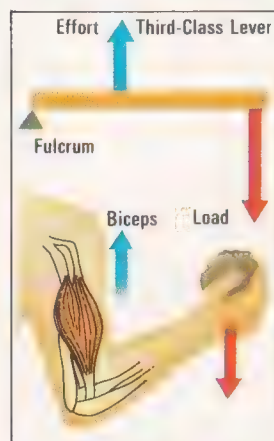
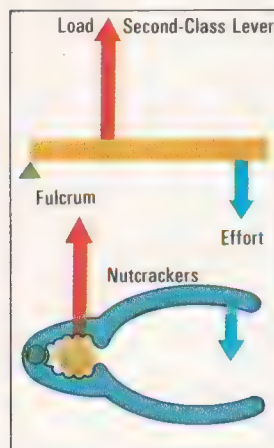
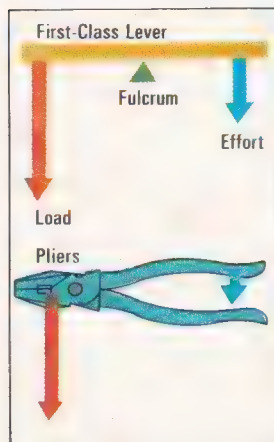
Above: Suppose a man boards a train at 3 pm and travels at 90% of the velocity of light. After an hour has passed on the train and his watch says 4 pm, he looks out of the window at a passing station. The Special Theory predicts that everything would appear to be squashed to half its length and to weigh twice as much, and time to be slowed to half its normal rate. A man on the scales would appear to be very heavy and the station clock would read 3.30 pm (left). However, from the platform, the moving train would appear shortened in length, its mass doubled and its time slowed down (right).

Below: From the General Theory of Relativity, Einstein predicted that stars would appear to change position when they are seen near the edge of the Sun. The Sun's gravity would cause light rays from the stars to curve as they pass near the Sun. The effect can only be seen during a solar eclipse, when the Sun's disc is obscured by the Moon.



Right: The pyramids of ancient Egypt were probably built by constructing a sloping ramp around them — an example of the use of an inclined plane.

Transferring Energy



Energy is not of very much use if it cannot be moved; the places where we need to apply force are not often the places where energy is being produced. The force produced in the cylinders of a car engine must be transferred to the wheels of the car; the lifting power of the biceps must be carried from the upper arm to the hand. In many cases, a connection such as a length of cable or a rod serves to transfer a force—pulling the plug out of a bath full of water without getting wet demands such a device, for example. But often a simple machine such as a lever or a pulley is required.

Simple machines not only transfer force from one point to another; they also enable a force to be increased in size. A small force applied to one part of the machine results in a greater force being produced at some other part of it. To do so, the machine does not create energy; that would be against the law of conservation of energy. Work, which is the expenditure of energy, is equal to force multiplied by the distance moved by the force as it does work. If the small effort moves a large distance while the greater force being produced moves a small distance, then the same amount of work is involved; no energy is being created. This is the basic principle governing simple machines. It is

easily demonstrated by considering the see-saw, which is a kind of lever. If a child sits at the end of one side and an adult sits halfway along the other side, then the child may find that his or her weight can easily lift the adult, who is probably twice as heavy. The effort applied multiplied by its distance from the pivot is equal to the force produced times its distance from the pivot; that is, the child can balance an adult who is twice as heavy because he or she is sitting twice as far from the pivot of the see-saw. Archimedes realized this principle of the lever and is reputed to have said 'Give me a place to stand on and I will move the world', meaning that if he had a lever long enough and a point on which to pivot it, he could in theory move the world.

All levers increase force by this principle, but they do it in three different ways. The see-saw is an example of a first-class lever, in which the pivot or fulcrum is between the effort applied and the force produced. So too are the crowbar and a pair of pliers. The second class of levers are those in which the fulcrum is at one end and the force produced is between the fulcrum and the effort applied. Nutcrackers and bottle openers are second class levers. In third-class levers, the fulcrum is again at one end, but the effort is applied between the fulcrum and the force produced. Sugar tongs and the forearm are examples of levers of this class.

The wheel and axle is another kind of simple machine that involves circular motion. The effort moves in a circle of greater radius

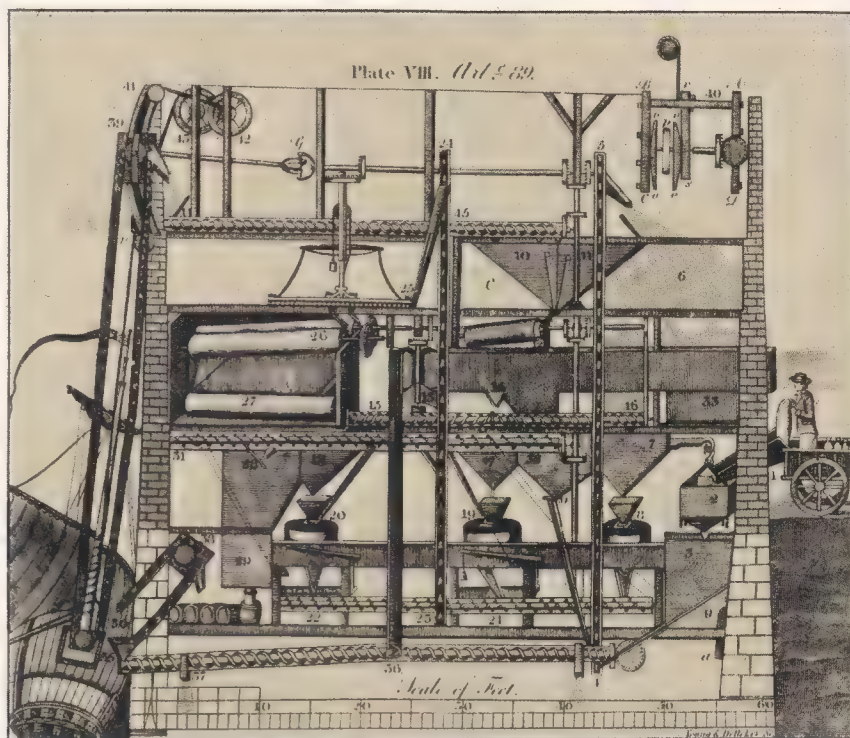
Left: The three classes of levers, with an example of each class. The small arrow indicates the effort applied and the large arrow the greater load that is overcome when the lever moves. In the case of the wheel and axle, the large arrow shows the greater force produced.

than the force produced. The spanner is an example, and so too is the screwdriver. The wheel and axle is in fact a form of lever, the fulcrum being the centre of rotation.

The inclined plane has long been known as an aid to work. Pushing or rolling a heavy object up a sloping plank or ramp is much easier than lifting it to the same height. The increase in force produced depends on the slope of the inclined plane. A screw is an example of the inclined plane, the thread of the screw simply being an inclined plane turned into a helix. Its use in transferring force can be seen in the screw jack, in which a heavy car is raised by turning a handle. The handle has to be turned many times to raise the car a small amount, enabling the arm to lift a heavy car.

Pulleys are very convenient machines for raising heavy loads. The force produced depends on the arrangement of pulley wheels in the pulley system.

The ratio of the force produced to the effort applied is called the *mechanical advantage* of a simple machine. For example, a pulley system with a mechanical advantage of 4 will raise a load weighing four times that which could be lifted directly by the effort. The ratio of the distances through which the effort applied and the force produced both move is called the *velocity ratio*. In some pulley systems, it may simply be equal to the number of strings supporting the load. The useful work got out of a machine divided by the work put into it is called the *efficiency* of the machine. The efficiency is also given by the ratio of the mechanical advantage to the velocity ratio

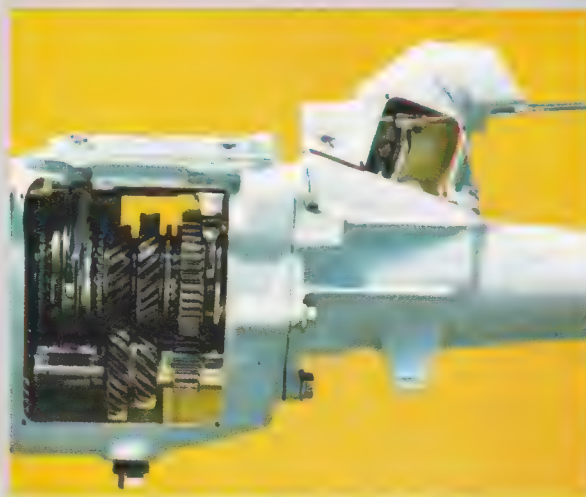


and is expressed as a percentage. No machine ever has an efficiency of 100% because some work is done in overcoming friction when the machine is used.

Hydraulics (see page 59) is a very convenient method of transferring force because the force produced can be taken to any point where it is required. Hydraulic systems obey the basic principles of simple machines. So too do gears, which easily transfer rotary motion.

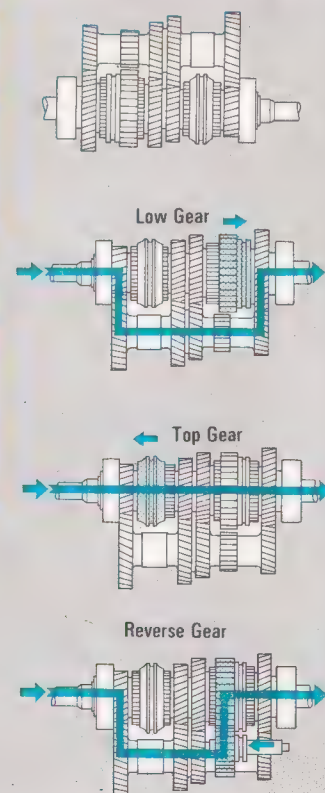
Above: An automatic corn mill built in 1791. The corn is carried from one part of the mill to another by Archimedes' screws. This screw is a simple machine that works on the principle of the inclined plane. It consists of a screw rotating inside a tube. It is said to have been invented by the Greek scientist Archimedes, who lived in the 200s bc.

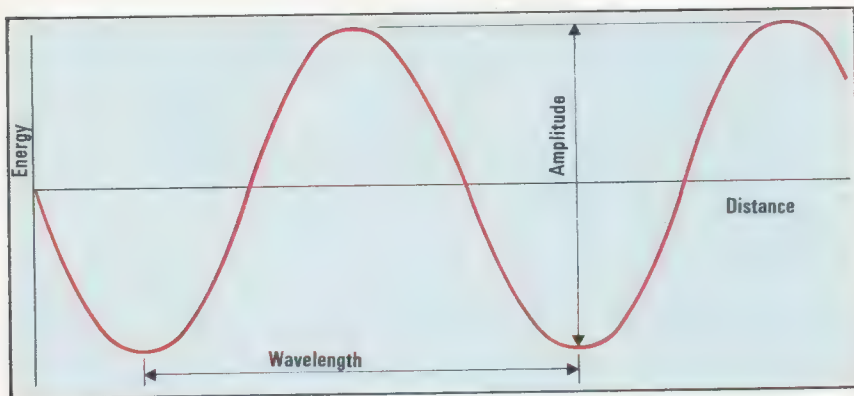
Below: Gear wheels turn at different speeds in proportion to the number of teeth they possess. The small wheel will turn at four times the speed of the large wheel if it has one quarter the number of teeth.



Above: A view of the gear box of a modern car with the gear lever (upper right).

Right: The gearbox transmits power from the engine to the mainshaft connected to the wheels, but changes the velocity ratio. At low gear, the engine turns the mainshaft at a slower speed than in top gear, giving greater power to climb hills. In top gear, the force is transmitted directly through the gear box; at low gear, it goes through the lower gear wheels. To reverse, a gear wheel called an idler is brought into play and turns the mainshaft in the opposite direction.





Above: The wave form of a wave is a graph of its amplitude against distance from a given point. The amplitude is the maximum displacement over one complete vibration, and the wavelength is the distance between corresponding points in successive wave forms.

Wave Motion

Energy does not always have to be carried mechanically from one place to another. Some forms of energy flow or move of their own accord. Electrical energy flows through a wire, for example, and radiant energy such as light spreads out through space from its source. Radiant energy is one of several forms of energy that travel in waves. Wave motion is very important; a knowledge of the way in which waves move is necessary to understand fully how we see and hear, for example.

A wave is basically a vibration of energy. As a wave passes a point, it produces a constant rise and fall of energy. A boat in the sea bobs up and down as waves pass, its potential energy constantly increasing and decreasing. Although the water appears to move with a wave, there is in fact no such movement. The particles of water just move up and down in a vibrating motion as the wave passes. Sea waves are produced by the wind blowing on the surface of the sea, and they carry some of the energy of the wind.

Light and other forms of radiant energy are made up of vibrating electric and magnetic fields and are therefore generally known as *electromagnetic waves*. They may be produced by the acceleration of electrons, and they are received in various ways. Light waves produce vision of course and heat rays produce heat; radio waves produce an electric signal in electrical conductors.

Sound travels in a wave motion through any substance. Sound waves are vibrations of molecules; they are produced by a vibrating

surface and cause identical vibrations in any surface the sound waves meet. We hear because our ear drums vibrate with sound.

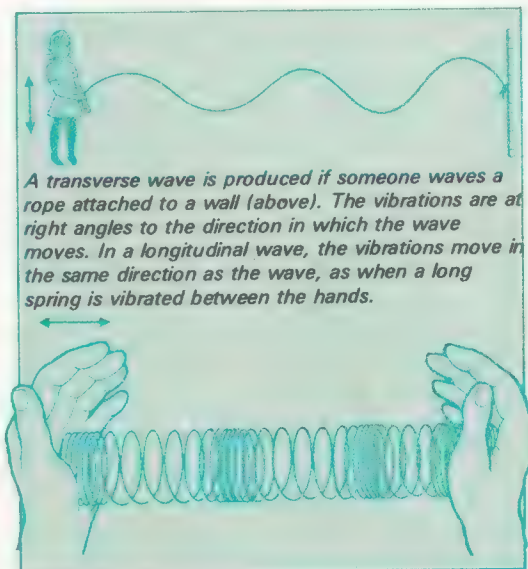
All waves have two basic properties: *amplitude* and *frequency*. Amplitude is simply the degree of energy change that occurs as a wave passes. A wave with a large amplitude consists of large vibrations of energy; in a sea wave, the waves are high and in sound, the vibrations are large and the sound is loud. In radiant energy, greater amplitude produces greater intensity; light is brighter and heat rays are more warming. Frequency is the rate at which complete vibrations of the wave pass. A complete vibration is a change in energy from maximum to minimum and back to maximum again. Frequency is measured in hertz; a wave of 100 hertz passes at the rate of 100 vibrations per second.

Waves move at a constant velocity; light moves too fast for the eye to detect its motion, but the movement of sound waves is noticeable over long distances. The distance over which



Above: A sea wave of great amplitude (height) carries surfers to the shore.

Below: An earthquake occurs where seismic waves — vibrations in the rock — reach the Earth's surface and cause it to vibrate.



A transverse wave is produced if someone waves a rope attached to a wall (above). The vibrations are at right angles to the direction in which the wave moves. In a longitudinal wave, the vibrations move in the same direction as the wave, as when a long spring is vibrated between the hands.

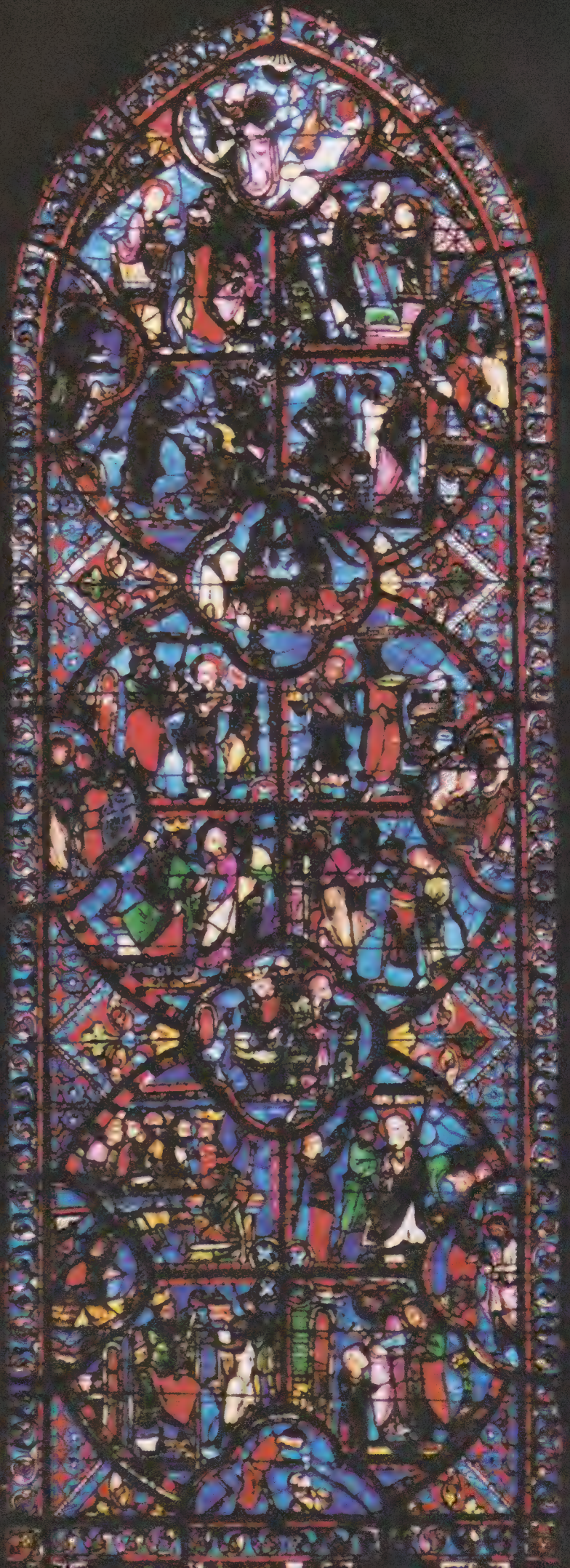
one complete vibration of energy occurs is called the *wavelength* of the wave and the greater the frequency, the less the wavelength and vice-versa. In fact, the velocity of a wave is equal to its frequency multiplied by its wavelength.

We perceive the frequency of a wave in various ways. Light of different frequency appears a different colour, whereas sound of different frequency has different pitch.

Some waves need a medium in which to travel; sound travels through air, water, metal or any other substance. Sea waves move over the oceans and seismic waves move through solid rock, causing earthquakes when they meet the surface. Electromagnetic waves need no medium and travel through empty space. Electromagnetic waves and sea waves are *transverse waves*, meaning that the vibration in energy takes place at right angles to the direction in which the wave is moving. Sound waves are *longitudinal*: molecules vibrate in the same direction as the wave passes. Seismic waves are of both kinds.

The Electro- magnetic Spectrum

Light is one of the radiations of the electro-magnetic spectrum. In a myriad of colours, it conveys to us the wonder of the world around us. We put the other unseen radiations to many uses — from exploring the universe to looking within ourselves.



The Electromagnetic Spectrum

If you place a glass prism in sunlight, you will find that a band of coloured light is produced. The white sunlight is split up into a spectrum of several colours. Like the colours of the rainbow, which is a natural spectrum, the colours range from red through orange, yellow, green and blue to violet. If a thermometer is placed just beyond the red end of the spectrum, it will show a slight rise in temperature. This is because the Sun's light contains invisible heat rays that lie beyond red in the spectrum and are consequently known as infra-red rays. Other kinds of detectors will show that there are more invisible rays beyond the infra-red; first come microwaves and then radio waves. Other invisible rays lie beyond the violet end of the spectrum—ultra-violet rays, X-rays, gamma rays and cosmic rays. In fact, visible light makes up only a very small section of this great spectrum of rays.

These rays have many different uses and may seem to be entirely different. But they all belong to one great family of rays called electromagnetic radiation. This radiation is

composed of vibrating electric and magnetic fields, and it travels in a wave motion through empty space and through transparent substances. For example, glass and water are transparent to light just as our flesh is transparent to X-rays and the walls of our homes are transparent to radio waves. The whole electromagnetic spectrum is made up of energy that moves in a wave motion at a fixed velocity (that of light). The only difference between the various kinds of rays is their particular wavelength—the distance between each maximum of energy as the wave passes. The range of wavelengths is enormous—from less than a hundred-million-millionth of a metre for cosmic rays to thousands of metres for radio waves. Light occupies the very small wavelength band of 4 to 7 ten-millionths of a metre. The various rays may also be identified by their frequency—their rate of vibration—as well as by wavelength. Electromagnetic frequencies vary from ten thousand vibrations a second for radio waves up to a million million million million vibrations a second for cosmic rays.

Right: Light from the visible surface of the Sun originates as a continuous spectrum of colours (top) that combine to give white light. However, close examination of the Sun's spectrum reveals the presence of dark lines (bottom). This happens because certain elements absorb certain wavelengths as light passes through the Sun's atmosphere. This kind of spectrum is called an absorption spectrum. Each element produces a set pattern of lines and the absorption spectrum therefore identifies the elements present in the Sun's atmosphere. The elements in the atmosphere also emit light at the same wavelengths, giving an emission spectrum (centre).



Above: A line of radio telescopes detects radio waves from the heavens. The telescopes are connected together to make them more sensitive.

Right: Radar waves reflected from aircraft approaching an airport produce signals on a radar screen and show their location in relation to the runways.

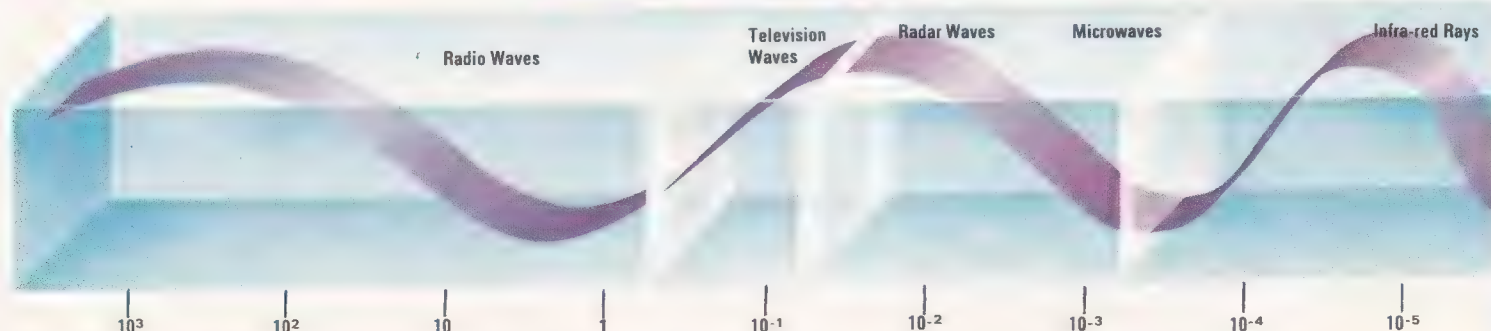


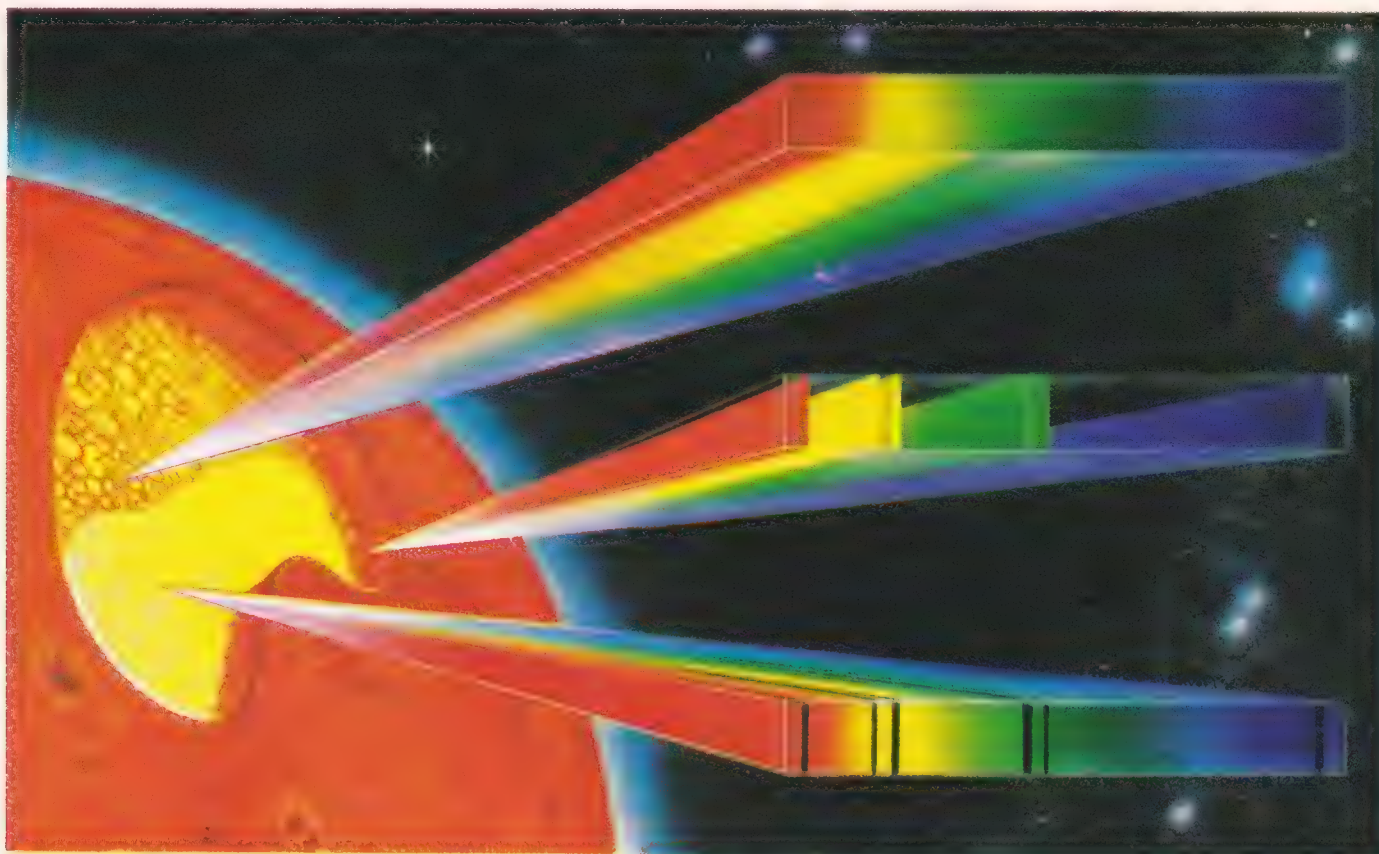
Below: Infra-red aerial photography distinguishes forests, fields, deserts and built-up areas by the varying amounts of heat they emit.



Above: Fireworks produce bursts of visible light of many colours in the night sky.

Below: The electromagnetic spectrum.





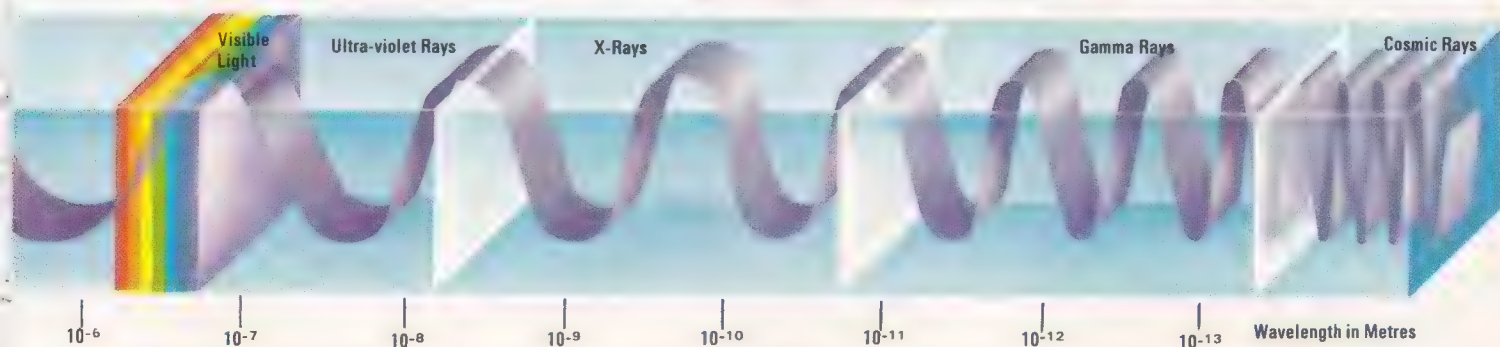
Right: Nuclear explosions produce intense beams of gamma rays. These rays cause radiation sickness and are very harmful. Heavy shielding around nuclear reactors absorbs gamma rays.

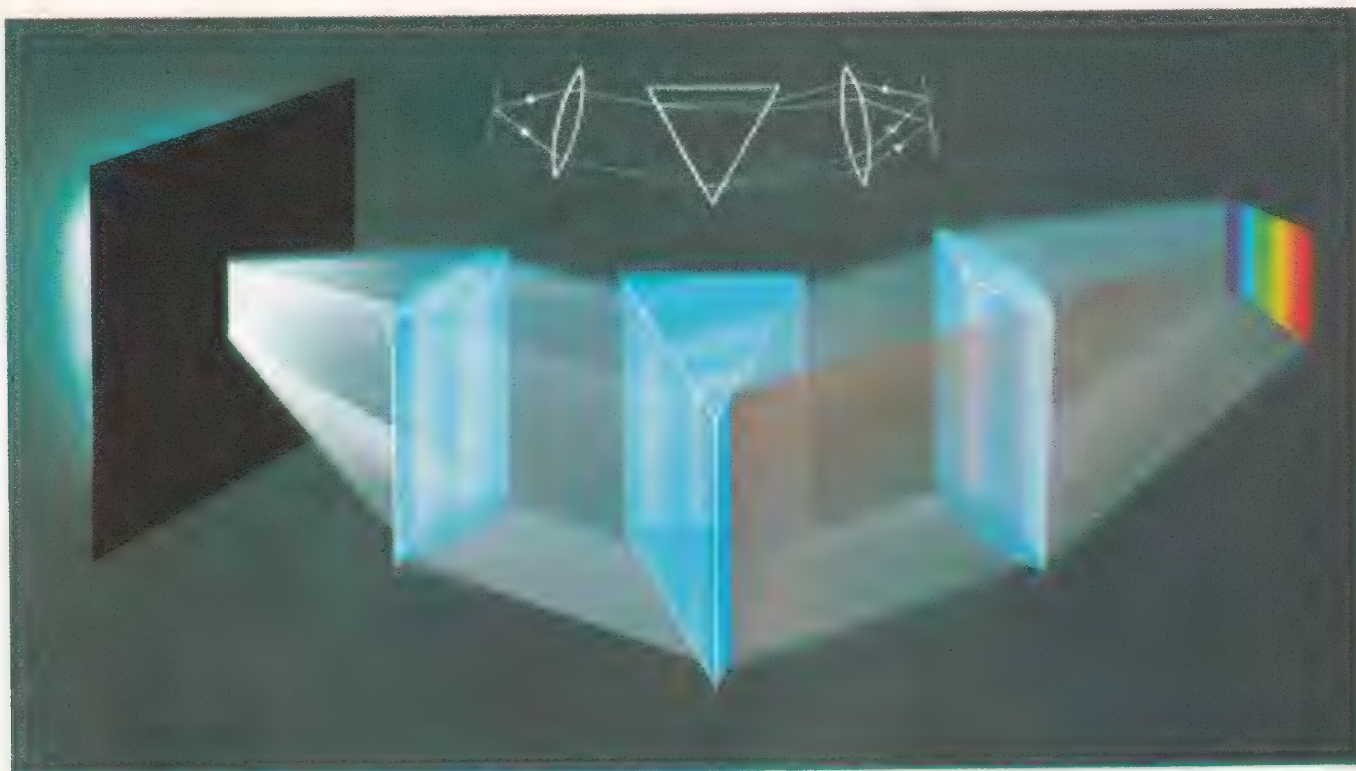


Above: Ultra-violet light from the Sun tans the bodies of holiday makers.



Right: X-rays penetrate flesh and can be used to examine the bones in the body.





The Nature of Light

Sir Isaac Newton found fame at the early age of 23 when, in 1665–6, he discovered that white light can be split by a prism into a spectrum of colours. His discovery marked the beginning of centuries of investigation into the nature of light, as people tried to find out what light consists of, how fast it travels and how it is produced.

Newton proposed that a ray of light is made up of a stream of minute particles, or corpuscles. He noticed that light travels in straight lines and bounces off mirrors in a perfectly regular way. The corpuscular theory easily explained this behaviour of light, but Newton was aware that other kinds of behaviour were not easily accounted for by the theory. When light passes the edge of an object, it bends around the edge to a slight degree. This effect, which is called *diffraction*, could not be explained if light were composed of corpuscles.

In 1690, Christiaan Huygens showed that no difficulties arose if light consisted of waves. But his ideas lay neglected for a century, overshadowed by those of Newton. Then, in 1803, Thomas Young discovered the effect known as *interference* (see page 92), which is a property of all waves. Then Augustin Fresnel provided an explanation for the polarization of light by using the wave theory, and Huygens was at long last vindicated.

Meanwhile, other scientists had been trying to measure the velocity of light. This problem had defeated Galileo, who tried to do it with

the aid of two men on hilltops some way apart flashing lamps at each other. Light moves far too fast for its velocity to be detected in this way, but many people thought that light had an infinite velocity and moved instantaneously. However, nearly a century later, in 1676, Olaf Roemer obtained a value for the velocity of light. He was able to find out the time it took light to reach Earth from Jupiter and showed that light has a great but finite velocity. Improved methods were developed by James Bradley in 1728, who found that the directions of stars are related to the velocity of light, and by Armand Fizeau and Jean Foucault from 1849 on. They were able to measure accurately the time it takes light to travel to a distant mirror and back.

All these discoveries were crowned by the astonishing work of James Clerk Maxwell. In the 1860s, he showed that light consists of a wave of vibrating electric and magnetic fields. The vibrations take place at right angles to the direction of motion and to each other. Maxwell predicted mathematically the velocity with which such a wave motion would move, and this velocity was equal to the results obtained for the velocity of light. The value now accepted for the velocity of light is 299,792.5 kilometres a second. Maxwell went on to show that light must be only a small part of a great electromagnetic spectrum and that other rays must exist with the same velocity. Infra-red and ultra-violet rays were already known and, by the turn of the century, radio



Above: A spectrum of white light consists of the colours of the rainbow. If these colours are painted on a card (top) and the card is then spun rapidly, the colours mix together in the eye and give white (bottom). This proves that white light is a mixture of colours.

Left: A spectrum of colours is formed when a beam of light passes through a prism. In a spectrometer, the light first passes through a slit and then an image of the slit is formed by passing the beam through two lenses. In between the lenses, a prism splits up the light into its basic colours. A series of images of the slit in the different colours forms, overlapping to give the spectrum.

waves, X-rays and gamma rays had been found. Maxwell also concerned himself with the production of electromagnetic waves, and suggested that they were caused by the acceleration of an electric charge. We now know that light and other electromagnetic waves are given out when an electron leaves its orbit around the nucleus and moves to a closer orbit. When an atom gains energy, for example by absorbing light or heat, electrons move to more distant orbits. They may remain there for some time, storing the energy they receive, until they jump back to closer orbits and give out the energy, as happens in luminous objects. Or they may jump back immediately—as when light is reflected from an object or when an object is heated and it glows.

The Quantum Theory

It seemed for some time that Maxwell had very neatly tied everything up and discovered all there was to know about light. But problems soon arose with the wave theory. Some new effects could only be explained by a return to corpuscles. In fact, Max Planck in 1900 suggested that *all* energy is made up of indivisible packets of energy called *quanta*. A quantum of light or other electromagnetic radiation is called the *photon*. Albert Einstein in 1905 then explained the photoelectric effect, in which some metals emit electricity when illuminated, as in the solar cell, by simply assuming that each photon causes the emission of an electron. However, other effects such as interference could still only be explained by the wave theory, and now scientists look on light and other electromagnetic radiation as existing as both particles and waves. Moving particles were later found to have wave properties; electron beams behave like waves in the electron microscope, for example.

THE NATURE OF LIGHT



Light can be thought of as a wave motion in which regular vibrations of energy occur. The height or amplitude of the wave varies with the brightness of the light. The wavelength (distance between successive crests of the wave) varies with the colour of the light.



Light may also be regarded as a stream of particles of light energy (above). Each particle is called a quantum or a photon. The energy of each photon is related to the wavelength and therefore the colour of the light, a photon of blue light having more energy than a photon of red light. Combining the two views of light, we can think of light progressing in packets of waves, each packet corresponding to a photon (below). The energy of the photon will depend on its frequency.

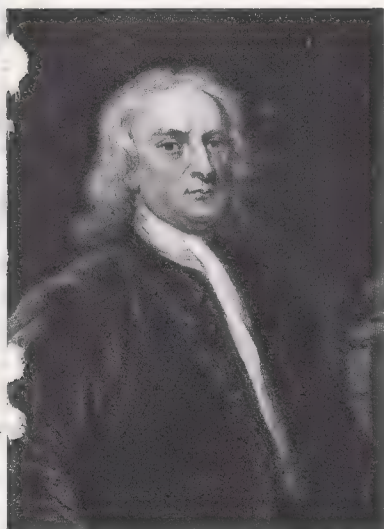


Electric Vibrations



Magnetic Vibrations

Light waves consist of two vibrations of energy, both at right angles to each other and to the direction of the wave. In one plane, vibrations of an electric field take place; and in a plane at right angles, vibrations of a magnetic field take place.



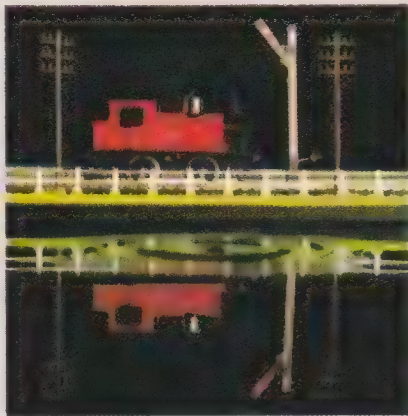
Sir Isaac Newton



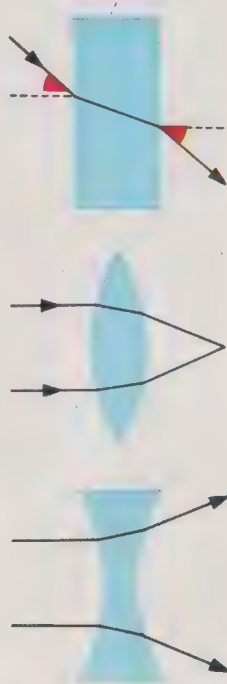
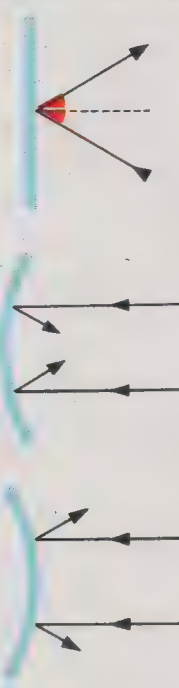
Right: A satellite, seen here before launch, is covered with solar cells that convert sunlight into electricity to power the satellite's instruments.

Planck's theory states that the energy of a quantum is proportional to its frequency. The colour of light depends on its frequency, so that blue light has more energy than red light. This explains why a poker glows first red, then yellow and finally white when heated in a fire. As it gets hotter, it receives more energy and produces radiation of greater energy. As it does so, the light moves through the spectrum towards the blue end. When it is glowing with all colours, these combine to give white as in sunlight.

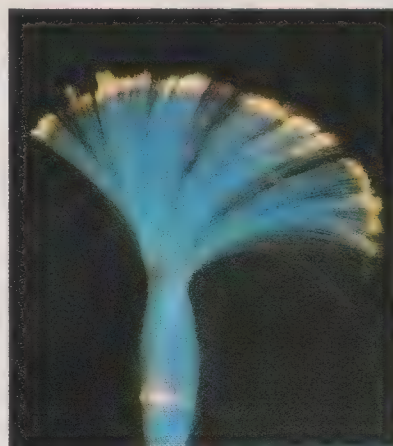
Bending Light



Reflection occurs because light rays bounce from surfaces. A plane mirror (above) produces an image the same size as the object. In all mirrors, rays are reflected so that the angle of incidence equals the angle of reflection (top right). Concave mirrors make light rays converge, producing a magnified image of a near object (centre right), and convex mirrors cause rays to diverge, giving a diminished image (bottom right).



Refraction occurs where light rays pass through surfaces. On entering a denser medium, rays are bent towards the normal (top left). As they leave, the rays bend back again, leaving at the same angle as they entered. By bending light rays, refraction causes images to be displaced, as when objects are seen through water (above). Lenses work by refraction, causing light rays to converge or diverge, producing magnified or diminished images accordingly.



Fibre Optics depends on the principle that a light ray striking a surface at a large angle of incidence will be reflected from the surface. In this way light rays will travel along glass or plastic fibres, being continually reflected from one wall of the fibre to another (above). A group of fibres will carry light from one end to the other, producing a spray of light at the fibre tips (left).

We see objects because light travels from them in rays to our eyes. Our eyes always assume that each light ray has taken a straight line in its path to our eyes. But a mirror or lens may bend the light; even so, our eyes still believe that the light has taken a straight line and they see an image of the object in this direction. For example, at some time in our lives, we must all have walked towards—or even possibly into—a mirror without realizing that we were approaching an image and not a real scene. The mirror simply changed the direction of the light reaching our eyes and confused our senses.

The behaviour of light in optical instruments depends on two effects—*reflection* and *refraction*. Reflection is the bouncing of light off surfaces, and refraction the bending of light as it passes through a surface. Mirrors work by reflection and lenses by refraction.

In fact, all objects reflect light (except for the deepest black surfaces, which absorb light). If they did not do so, we would not be able to see them. Coloured objects reflect some light and absorb the rest, whereas white and shiny surfaces reflect all the light that strikes them. Reflection works by two simple laws. Imagine a line drawn perpendicular to the surface at the exact point at which a light ray strikes the surface. This line is called the *normal*. The angle between the *incident* (incoming) ray of light and the normal is called the *angle of incidence*, and the angle between the reflected ray and the normal is the *angle of reflection*. The two laws of reflection state (1) that the incident ray, normal and reflected ray all lie in the same plane; and (2) that the angle of incidence equals the angle of reflection.

Most surfaces are rough, so that the normals do not all point in the same direction and the rays are reflected away at various angles. This produces a dull appearance. But a smooth surface reflects all rays at the same angle; the surface appears shiny and acts as a mirror.

When we look into a flat, or *plane*, mirror, we intercept light rays reflected by the glass surface. These rays originally come from an object of some kind—ourselves if we stand directly in front of the mirror. We therefore see an image of the object in the mirror. Being flat, the surface does not distort the light rays and we see an upright image the same size as the object—but it is back to front, because the rays change sides as they are reflected. Curved mirrors also produce images. A mirror

that curves out towards the onlooker is called a *convex* mirror. It spreads out or diverges the rays as they are reflected, and this causes the image to appear smaller than the object. A driving mirror is often convex. A *concave* mirror curves inward and therefore converges the rays, producing a magnified image of an object close to it. A shaving mirror is concave.

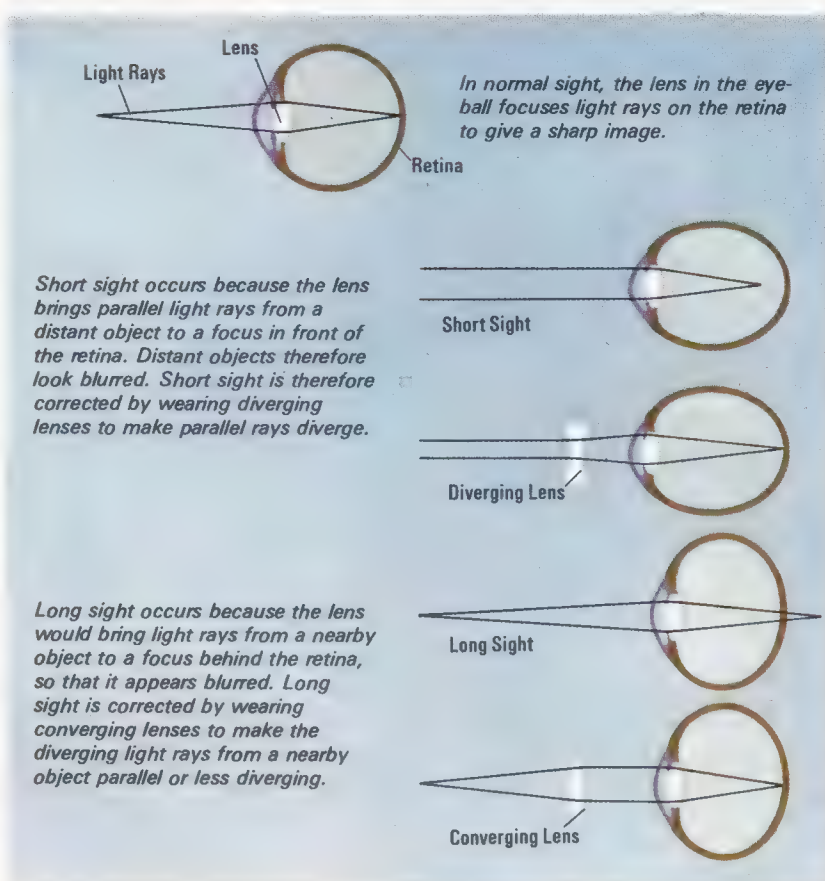
The above images appear to be behind the mirror. These kinds of images are called *virtual* images, because they only exist in our eyes. A concave mirror can form another kind of image that can be projected on a screen; this kind of image is called a *real* image. It is produced when rays of light leaving the same point on the object converge and come together again after being reflected by the mirror. The real image is formed at the point where they meet. Its size depends on the curvature of the mirror and on the position of the object, but, with a good mirror, it will be an exact and sharp image of the object. The mirror in a car headlight works in this way; it projects a magnified real image of the bright filament in the bulb onto the road ahead.

The Bending of Light

Refraction occurs when a ray of light passes from one medium to another—as from air into glass. Unless it travels perpendicularly to the surface (that is, along the normal), it will be bent. If it is entering a denser medium, such as from air into glass, it will be bent towards the normal. If it is leaving the denser medium, it will bend away from the normal. Refraction occurs because the speed of light is slowed slightly as it enters a denser medium. The amount of bending that occurs depends on the difference in the speed of light in the two media, and the angle of incidence is related to the angle of refraction (the angle between the normal and the refracted ray) by the *refractive index*. This is a set number for a given wavelength for each particular pair of media, and it is equal to the sine of the angle of incidence divided by the sine of the angle of refraction. This is known as *Snell's law*. The other law governing refraction states that the incident ray, normal and refracted ray all lie in the same plane.

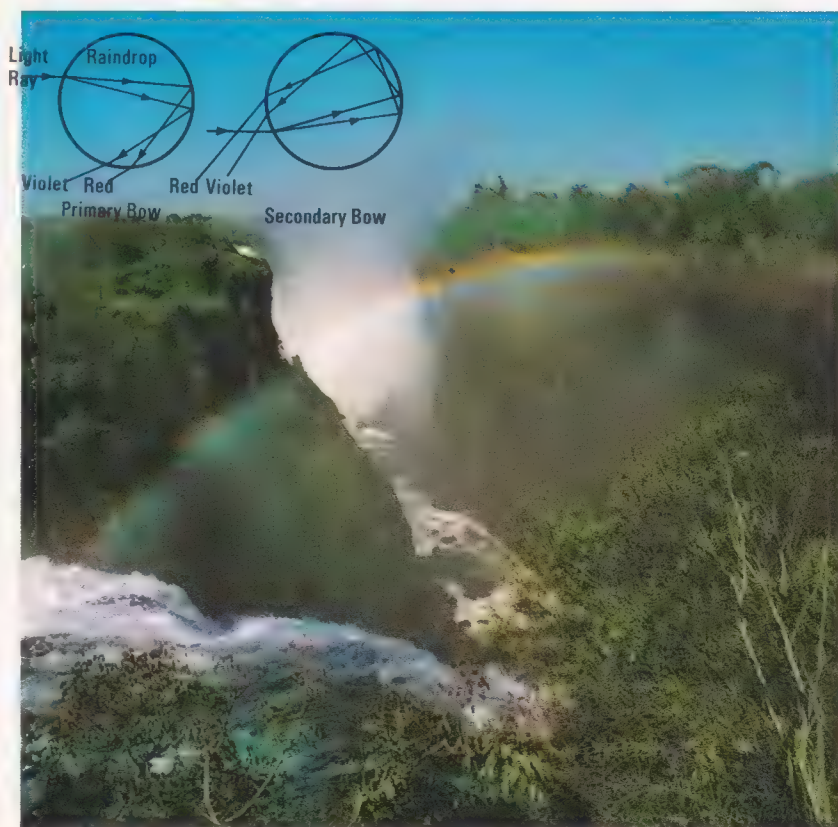
Refraction explains why a stick appears bent when placed half in and half out of some water. The rays coming from the immersed part are bent as they leave the water. The eye still assumes that the rays have travelled in a straight line, and sees an image of the stick displaced from its true position. For the same reason, submerged objects appear to be less deep than they actually are.

Lenses work by bending light rays by refraction to produce images. A converging lens makes the rays from an object converge so that they meet and produce a real image or, on looking through the lens, a virtual image. Diverging lenses make rays diverge so that a real image cannot be formed. On looking through them, a small virtual image of the object is seen.



A rainbow forms because sunlight is refracted by raindrops and split up into a spectrum of colours. The brightest or primary bow is produced when rays are reflected once inside the

drops (left insert). A less bright secondary bow may also appear in which the colours are reversed, caused by double reflection in the raindrops (right insert).



Waves of Light

Light, like all other wave motions, spreads out in all directions from its source. A surface that is illuminated by light will act as another source, unless it is jet black. Light is therefore reflected back from a barrier, just as sound echoes off a cliff and a water wave rebounds from the side of a bath. But the edge of the barrier will be illuminated too, and light will spread from the edge behind the barrier. Some light therefore bends around the edge as it passes the barrier. This effect is called *diffraction*. Diffraction of sound explains why you can hear someone speaking behind a garden wall even though there are no surfaces nearby to reflect the sound to you. The sound waves diffract over the top of the wall.

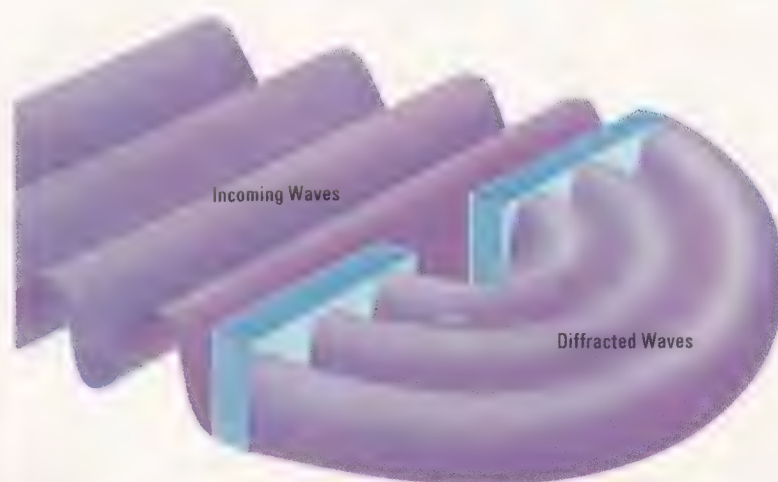
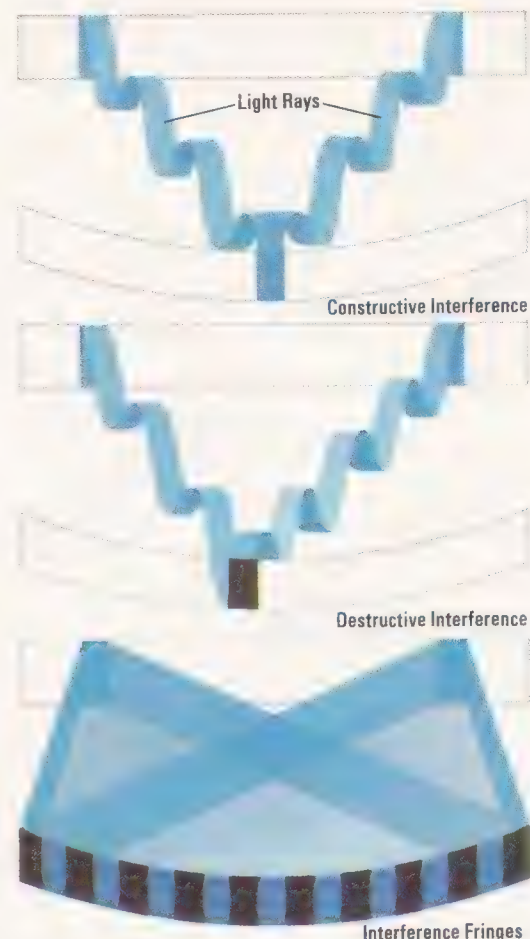
Another property of waves is the effect that occurs when waves meet. If two water waves meet so that both crests run together, then a large wave will result. But if they meet so that the crests of one always coincide with the troughs of the other, then level water will result as the two waves cancel each other out. This effect of waves is known as *interference*. Constructive interference occurs when waves reinforce each other and destructive interference where they cancel out.

Interference occurs in all kinds of wave motions. In sound, it produces beats, which

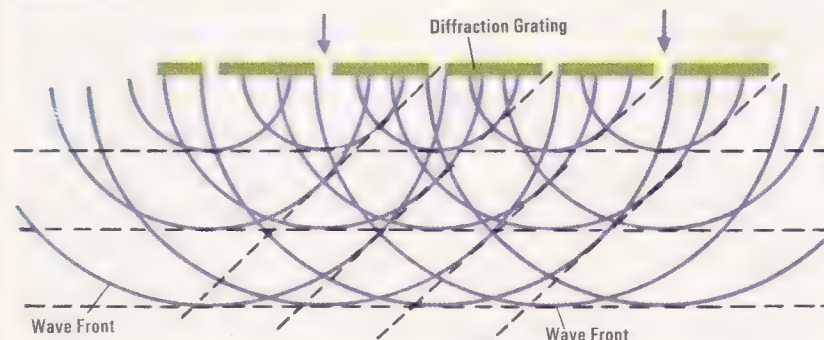
The spectra of a cluster of stars show varying patterns that depend on the elements present in the stars. Many heavenly bodies have spectra in which the pattern of lines is shifted towards the red end. This is a consequence of the Doppler effect and is caused by the bodies moving away from us, 'stretching' the light waves and increasing their wavelength.



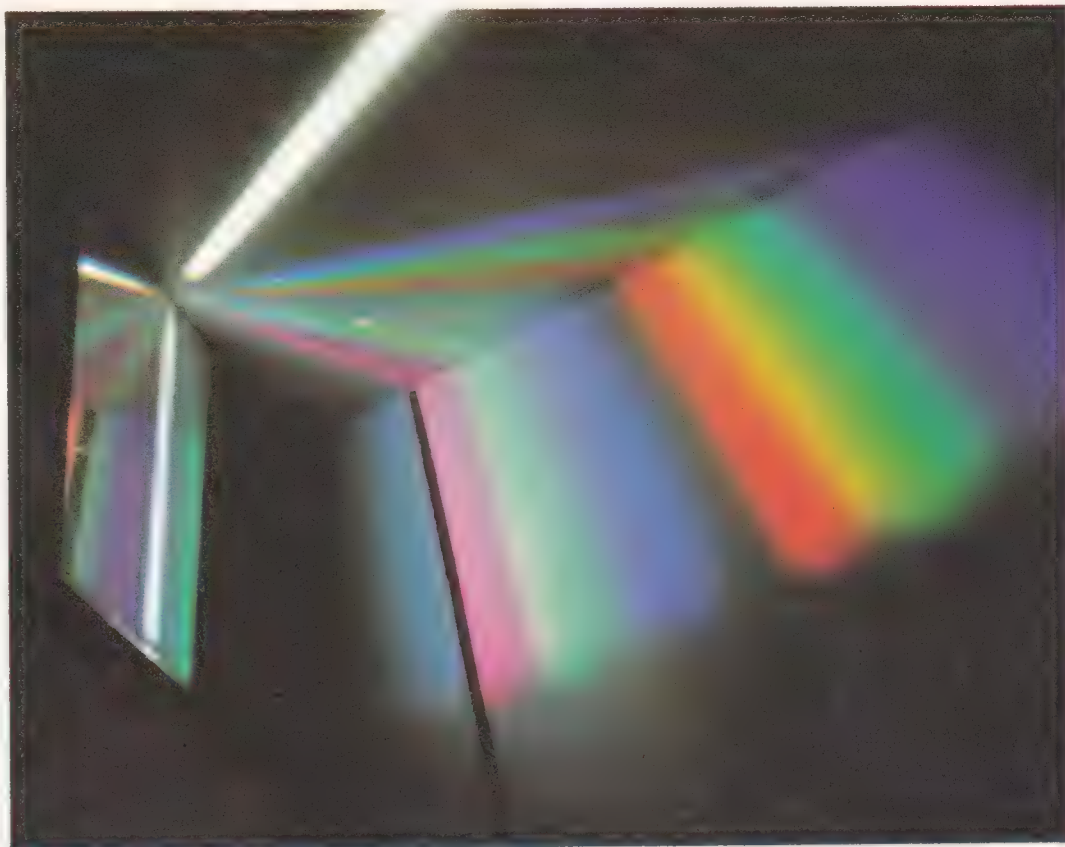
Right: Interference occurs when two light rays meet. If two identical rays meet so that the wave crests coincide, they will reinforce each other, producing a bright region on a screen (top). But if they meet so that the crests of one coincide with the troughs of the other, then they will cancel each other out, producing a dark region (centre). Identical rays are made by splitting a beam of light into two. Where the two resulting beams meet, a pattern of light and dark fringes is produced by interference (bottom). The pattern depends on the wavelength of the light and the distance each beam travels to the screen.



Above: Diffraction occurs when any wave meets the edge of an object. The edge acts like a source of the waves, sending out new waves in all directions. In this way the waves bend around the edge. The effect is most obvious when a wave, such as a light ray, meets an opening about the same size as its wavelengths.



Right: A spectrum produced by the reflection of a beam of white light from a diffraction grating. Several separate spectra are produced; here, two complete spectra can be seen and the blue end of a third. A diffraction grating produces the colours in the reverse order to a prism, red being diffracted more than blue. With a prism, blue is refracted more than red.



A picture of a candle flame made with an interferometer, which can detect minute differences in wavelengths of light. The colour of the flame varies slightly from one region to another, and the resulting variations in the wavelength of the light produced give a picture of the structure of the flame.

Opposite: A diffraction grating consists of a fine grid or a polished metallic surface ruled with fine lines. When illuminated by parallel light, each opening in the grid acts as a source of spherical waves. The combined effect is to produce parallel wave fronts travelling in various directions. Each set of wave fronts can be brought to a focus on a screen. The diagram shows how two sets of wave fronts are formed as the envelopes of the spherical waves. Because each wavelength produces a beam in a different direction a spectrum can be produced.

are slow variations in loudness. In light, we would therefore expect interference to produce variations in brightness or simply patterns of light and dark, and this is what happens. However, it can also produce effects of colour.

To produce interference effects that can be seen, light beams from two sources must be in phase with each other. This means that the wave motion of the light rays in each beam must be identical. The light from two such sources is said to be coherent. Light from two separate sources is usually incoherent and in general does not produce visible interference effects. The simplest way to produce two coherent sources of light is to place two narrow slits in front of a single narrow slit that is itself in front of a source of light. Because they originate from the same source, the light beams from the two slits are coherent. If a screen is placed on the other side of the slits, a simple image of the two slits will not appear. Instead, because the waves interfere, a pattern of light and dark fringes will be seen. Where a bright fringe occurs, the two waves reinforce each other. In the dark fringes, destructive interference occurs and a maximum of one wave coincides with a minimum of the other. Although this part of the screen is illuminated by the light from both slits, it is in darkness.

Interferometers are instruments in which light waves are reflected by mirrors and made to interfere. Because the wavelength of light is so short, a minute movement of the mirrors causes a shift in the fringes produced. Interferometers can therefore be used to measure extremely small distances.

A diffraction grating makes use of interference on a greater scale. It consists of a

grid of very fine mesh or a mirror ruled with very fine lines. Diffraction occurs as light passes through or is reflected from the grating. A pattern of widely separated interference fringes results. The spacing of the fringes depends on the wavelengths of the light. Because colour is related to wavelength, the diffraction grating will separate the colours in the light. In short, it will act as a very good prism and produce a spectrum. The colours are reversed in order compared with a spectrum produced by a prism.

Interference effects are often seen. The play of colours in a soap bubble or oil film is caused by interference between rays reflected from both surfaces of the bubble or film. A spectrum can be seen in a reflection from a long-playing record or through the fine mesh of an umbrella because they act like a diffraction grating.

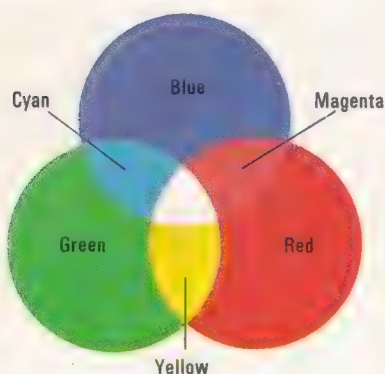
Polarization

Polarization is another effect of light waves. A polarizing filter acts like a light strainer and will only pass light vibrating in one particular plane. The light that emerges is called polarized light. It has many uses in science, including chemical analysis and the examination of models of structures to indicate stresses. If another polarizing filter is placed at right angles to the first, then it will not pass any light, because the polarized light produced by the first filter is vibrating in the wrong plane to get through the second filter. Polarizing sunglasses work on this principle. Light reflected from water or windows is polarized and the sunglasses contain polarizing filters that block this light, thereby removing glare.

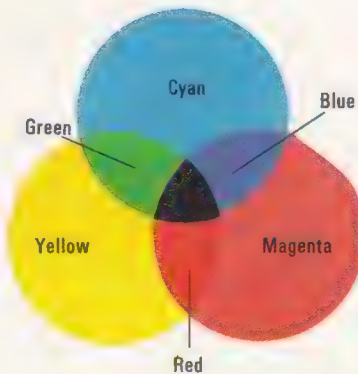
The Spread of Colour



Stage lighting consists of lights of the three primary colours which give a complete range of colour. The three primaries — red, green and blue — combine by additive mixing, combinations of two of them producing the three secondary colours — yellow, cyan and magenta. The inner pattern is caused by additive mixing of the coloured shadows of the dancer.



Additive mixing of colours occurs in coloured light, as in theatre lights and colour television. White forms by a combination of all three primary colours, and three secondary colours form by combining two primaries.



Subtractive mixing occurs in paints, inks and dyes. The three basic colours are the three secondaries of additive mixing. Combinations of two basic colours produce the three primaries, and all three basic colours combine to give black.

We often use the phrase 'all the colours of the rainbow' in describing something that is multi-coloured. There are indeed many colours in the rainbow, or the spectrum of sunlight, and each corresponds to a certain wavelength of light. Red has the longest wavelength and violet the shortest, and other colours range between them. But there are many colours that are not present in the rainbow—pink and brown for example. Where do they come from?

An object appears to have a certain colour because its surface reflects light of that colour. White light, or sunlight, is a mixture of all colours, and a red object appears red in white light because its surface reflects red but absorbs all the other colours in the white light illuminating it. Similarly a white object would appear red in red light, because its surface always reflects all the light illuminating it. If we looked at it in blue light, it would appear blue. But if we looked at the red object in blue light, it would appear black because the surface would be reflecting no light. This is why everything appears so lacking in colour beneath the orange glare of sodium-vapour street lights. The sodium light is of a single colour—yellow-orange—and surfaces either reflect this colour or absorb it, so that everything appears yellow-orange or black.

Coloured lights work in the same way. If we place a red filter over a white light, then the filter will absorb all colours except red; only red light passes through the filter, producing a red beam.

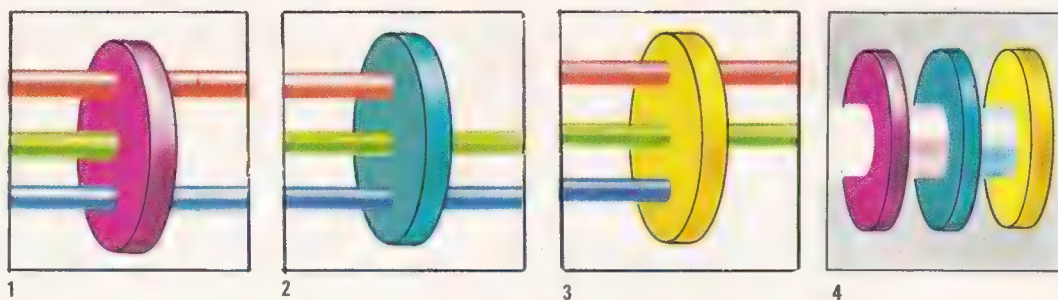
Few surfaces or filters absorb all but a single wavelength of white light. Most reflect or pass a mixture of colours, and these colours combine in the eyes to produce a vast range of colours.

It seems that the eye is mainly sensitive to three basic or primary colours—red, green and blue. Other colours are combinations of these three primary colours, and this is made use of in many forms of colour reproduction—television, for instance. There are two ways of mixing the primary colours together, additive and subtractive.

Mixing Colours

Additive mixing is done with sources of light—theatre lights or the glowing screen of a colour television set. If you look at a colour set close-to, you will see that the picture is made up of

Right: Colour filters produce colour by subtractive mixing in the same ways as paints and inks. White light is a mixture of red, green and blue. A magenta filter absorbs green and passes red and blue, which combine to give magenta (1). Similarly a cyan filter absorbs red and passes green and blue that combine to give cyan (2), and a yellow filter absorbs blue and passes red and green that combine to give yellow (3). All three filters together absorb all the colours in white light (4). The layers of dyes in colour photographs act as filters in the above ways.



a pattern of tiny dots or thin stripes of colour and that only three colours are present—red, green and blue. From a distance, the dots or stripes merge together to form a picture and the primary colours merge to give full colour. If all three colours are equally bright, then white is seen, becoming grey as the brightness is reduced. Black is an absence of all colours. Three secondary colours are produced by combinations of two primary colours—yellow from green and red, cyan from green and blue, and magenta from red and blue. All other colours are combinations of all three primary colours. The actual shade will depend on the brightness of each primary colour.

Subtractive mixing occurs when paints, inks or dyes are used. It is obvious that additive mixing does not work for these, as green and red make brown when you mix paints and mixing green, red and blue gives a muddy brown, not white. An absence of colour gives white—as long as you are working on white paper. The colour mixing is different because the pigments and dyes absorb colour from the

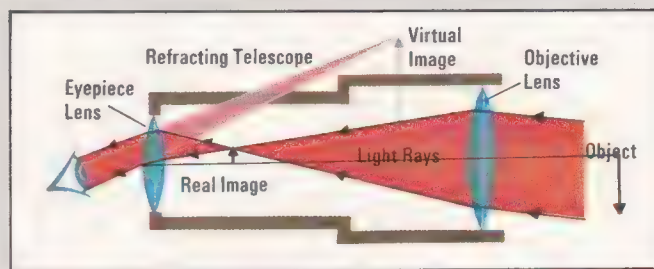
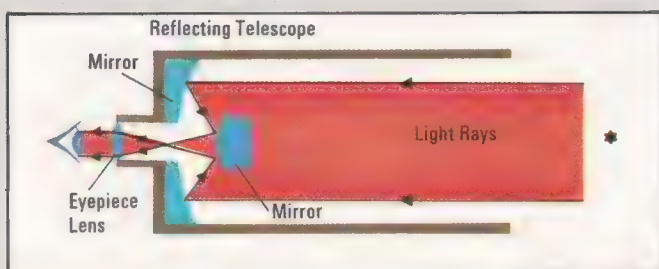
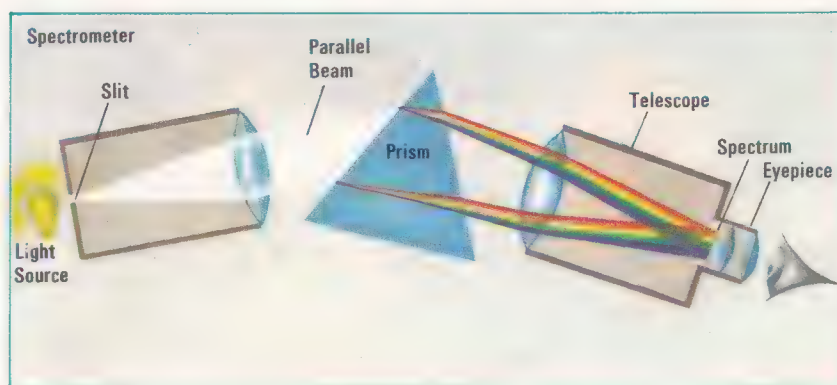
light illuminating them. Dyes or pigments of the secondary colours form the basic colours because they absorb single primary colours; yellow pigment absorbs only blue, leaving green and red to be reflected or passed, and to combine to give yellow. Cyan pigment absorbs red, leaving blue and green to combine; and magenta pigment absorbs green, leaving red and blue to combine. Red is obtained by mixing yellow and magenta, absorbing blue and green respectively and leaving only red to be reflected or passed. Mixing all colours equally results in the pigments absorbing all the colours in the illuminating light, and black is produced.

In colour photography, light passes through layers of yellow, cyan and magenta dyes in the film or surface of the print. In colour printing, a picture is made up of dots of yellow, cyan and magenta, which combine to give a full-colour picture at a distance. This method does not give a deep black, and so black is added as a fourth colour to produce a life-like result.

Below: The sky appears red at dawn and dusk because the Sun is low in the sky and its light passes through a greater amount of air than at other times. Dust in the air acts to scatter blue light and some green light from the sunlight, producing spectacular reds and yellows.



Optical Systems



Above: A pair of binoculars is simply a pair of small refracting telescopes.

Below: A microscope produces a magnified image of an object that is larger than its actual size.



Left: A telescope produces an image of a distant object that is larger than the object appears to the unaided eye. This is the Hale reflecting telescope at Mount Palomar in the United States. Its mirror is more than 5 metres across.

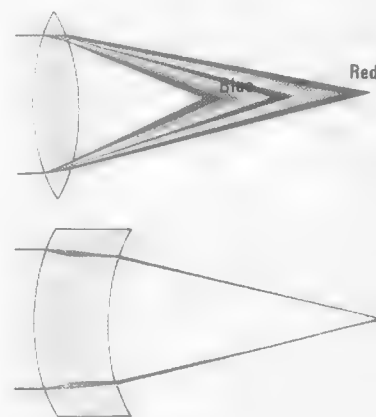
Optical instruments form images by bending light rays with mirrors or lenses. The rays leaving a single point on an object and striking a lens or mirror are bent. If they converge, a sharp real image forms at the point where they meet. When the object is at infinity—in practice, a long distance away—the image

Left: In a spectrometer, the spectrum of a source of light can be studied and photographed, yielding information about its composition.

Right: A simple convex lens does not give a sharp image because each part of the lens acts like a prism. Blue light is brought to a focus nearer the lens than

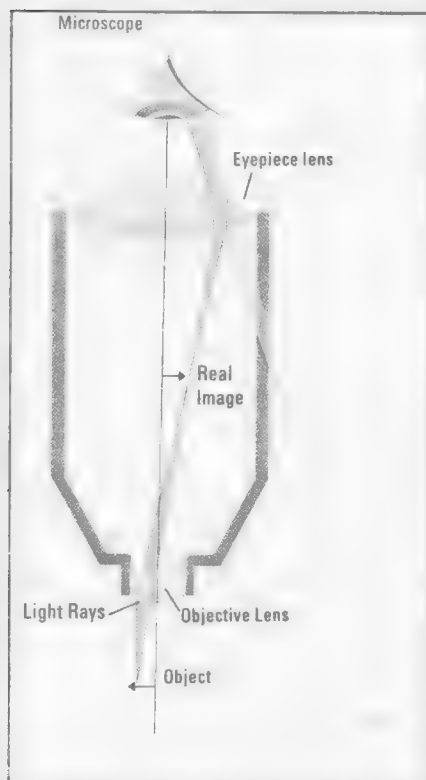
forms at a distance known as the focal length from the lens or mirror. If the rays diverge, a virtual image is seen at the point from which the rays appear to come. The object distance (u), image distance (v) and focal length (f) are related by the equation $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$.

red light, producing coloured fringes around the edges of an image (top). This kind of defect in a lens is called chromatic aberration, and it is partially eliminated by combining a concave lens with the convex lens. The concave lens makes the light rays of different colours converge instead of diverge and reduces the separation of the colours producing a sharper image (bottom).



VIRTUAL IMAGE SYSTEMS

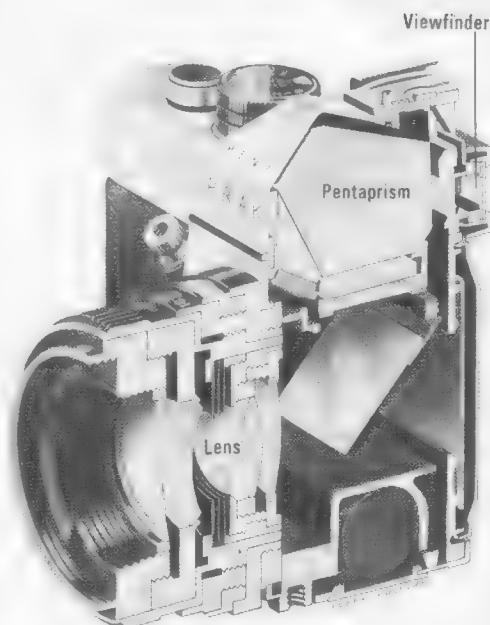
In optical instruments such as telescopes, binoculars and microscopes, a virtual image is seen. The objective lens either forms a real image that is then viewed through a magnifying lens to give a magnified virtual image or a magnified virtual image is formed directly by the lenses in the instrument. The formation of images can be shown by following the paths of light rays from the object being viewed to the eye. In the refracting telescope and microscope, rays leaving each point of the object (denoted by the black arrow outside the instrument) are focused by the objective lens to produce a real image (the black arrow inside the instrument). Only the rays that leave the top of the object are shown. The rays then go from the real image through the eyepiece lens to the eye. The eye believes that the light rays have come to it in straight lines, so that a large image (grey arrow) is seen at the point from which they appear to originate. In the reflecting telescope, a real image is formed by mirrors and then viewed through a lens.



REAL IMAGE SYSTEMS

In a camera, a real image is formed. The objective lens causes light rays from points on the object to meet at the surface of the film. The image is upside-down and back to front, but the film is turned round and the right way up when it is printed or projected, producing a life-like picture.

The single-lens reflex camera uses the same lens to produce a real image on the film and to view the scene before taking the photograph. When viewing, a mirror reflects the light rays through a pentaprism (five-sided prism) to the viewfinder. When the shutter release is pressed, the mirror rises out of the way, the shutter opens, and the light strikes the film.



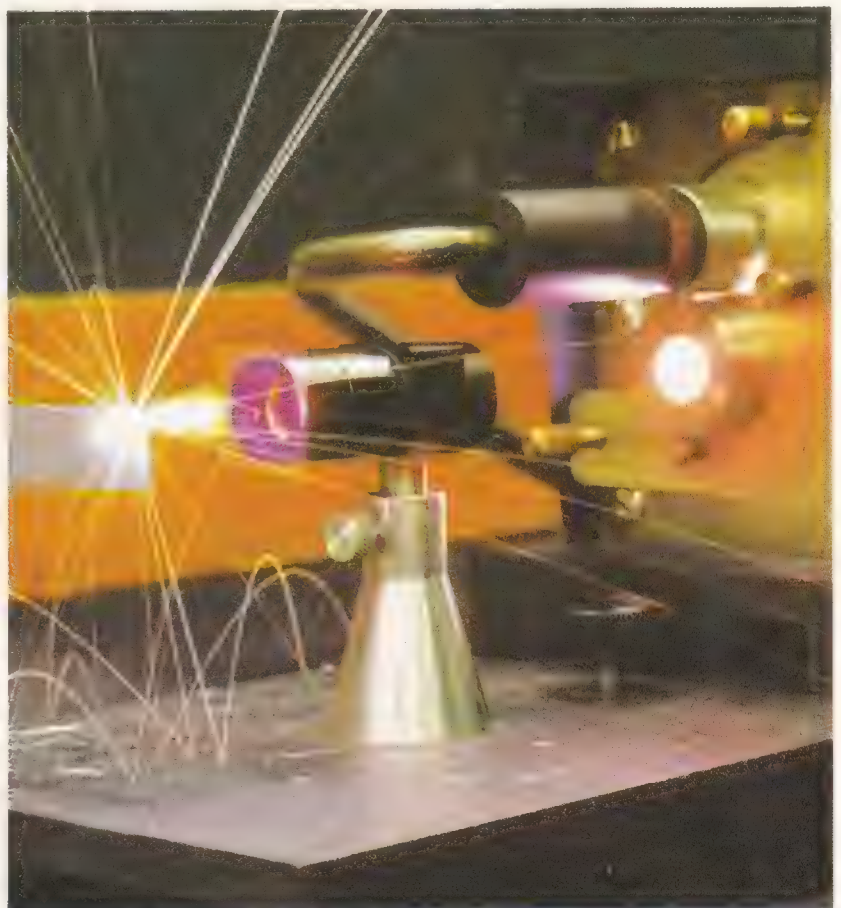
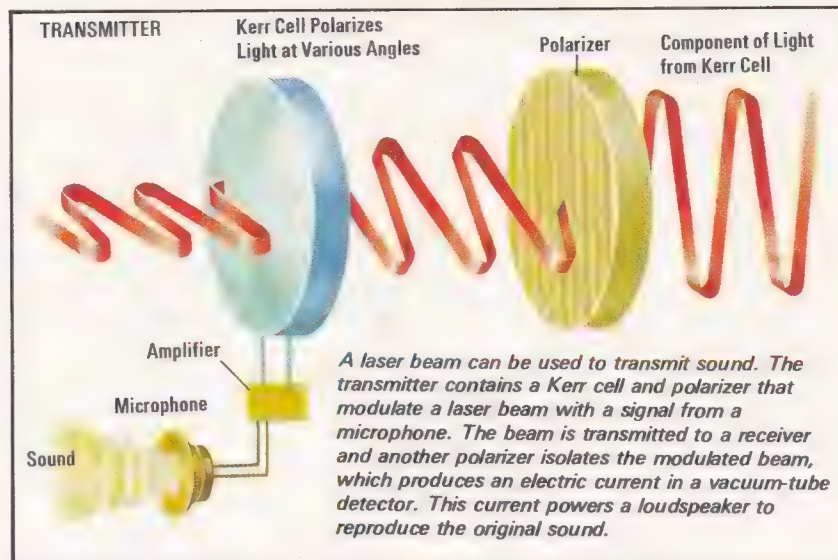
Lasers

The light produced by the laser is clearly no ordinary kind of light. Lasers can give an intense beam that will cut out patterns in steel plate and drill holes through diamond, the hardest substance known, to make dies for drawing wire. Military men have their eye on the laser to produce a kind of death ray. But so do medical men; laser beams can be used to drill teeth painlessly, and to repair damage to the retina of the eye.

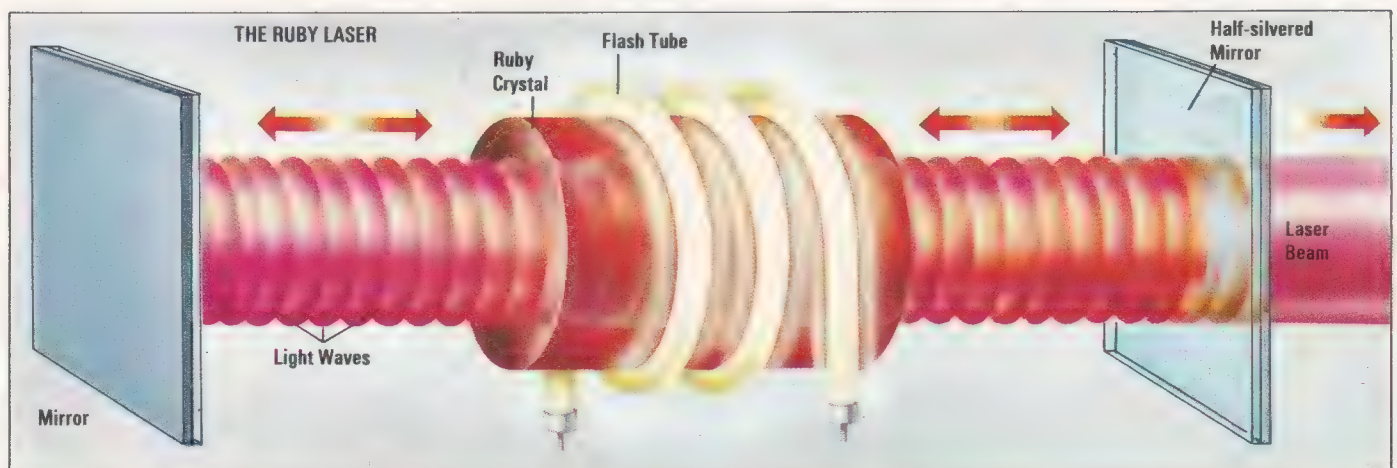
The name laser stands for Light Amplification by Stimulated Emission of Radiation; this mouthful does in fact describe how the laser works, but not why its light is so special. The laser can perform its many miracles because it produces a beam of coherent light. In this kind of light, all the waves vibrate exactly together. All the waves reinforce each other, producing light of great energy. The light is of a single wavelength, but each kind of laser produces its own wavelength. Some lasers produce invisible radiation, such as infra-red rays.

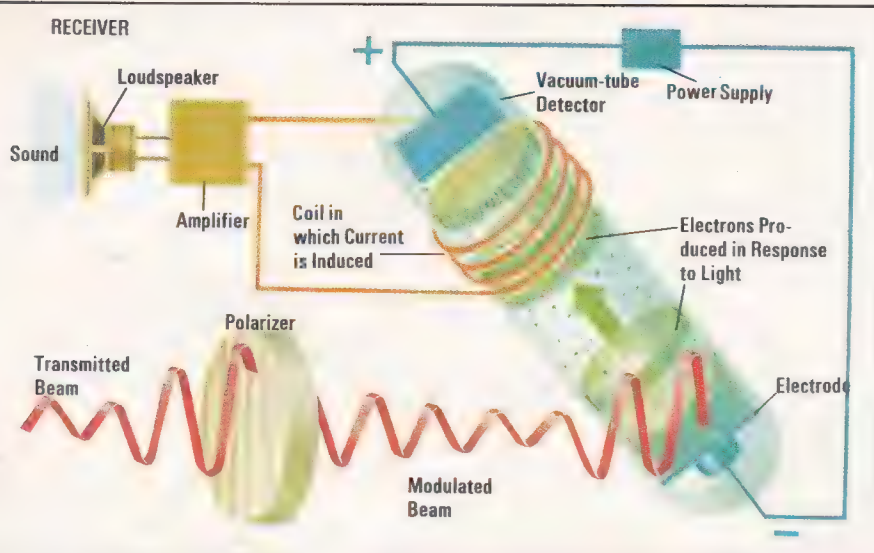
Light is produced when the electrons in an atom jump from one orbit around the nucleus to another nearer the nucleus. In doing so, they lose energy and this energy is emitted from the atom as light. To get up to the higher orbits, the electrons must be given energy. Now, if all the atoms in a substance can be made to produce light at the same time, then a pulse of coherent light will be produced. This happens in the laser.

At the heart of the laser is a crystal or tube of gas into which energy is pumped by surrounding it with a flashing light or a source of radio waves or electrons. More and more electrons in the atoms are raised to high-energy

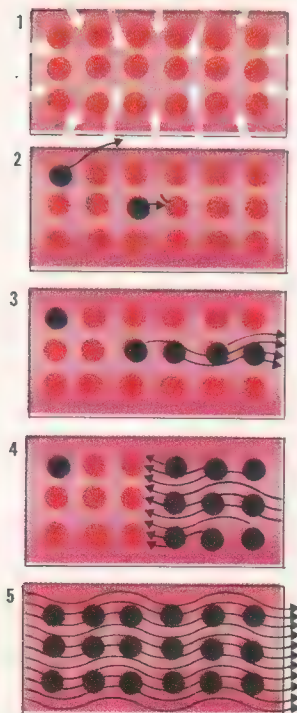


Right: Sparks fly as a laser beam cuts its way through a steel sheet. Below: The crystal at the heart of a laser produces an intense beam of light that is reflected between mirrors until it has sufficient intensity to leave through the half-silvered mirror.





Below: A laser crystal or tube contains atoms (1) that are excited, or raised in energy, by bombarding them with light or other radiation (2). An excited atom then suddenly loses its extra energy by producing light. This light strikes other excited atoms, causing them to lose their extra energy in the same way (3). The light produced is reflected between mirrors (4), causing a build-up of light as all the excited atoms lose their energy. Finally the light leaves through a half-silvered mirror at one end of the laser (5).



Right: Laser beams are used to detect movements of air over models of missiles or aircraft in wind tunnels.

HOLOGRAPHY

The most amazing effect produced by lasers is *holography*, by which solid images can be reproduced. Because laser light is coherent, it contains information on the shape of an object as well as its appearance when it is reflected from an object. This reflected light can be captured on a photographic plate to form a hologram. In ordinary light, it looks like a pattern of whorls. But when the hologram is illuminated by laser light, an image of the object is reconstructed with its shape. It not only appears solid but *is* solid; you can walk around the image and its perspective will change!

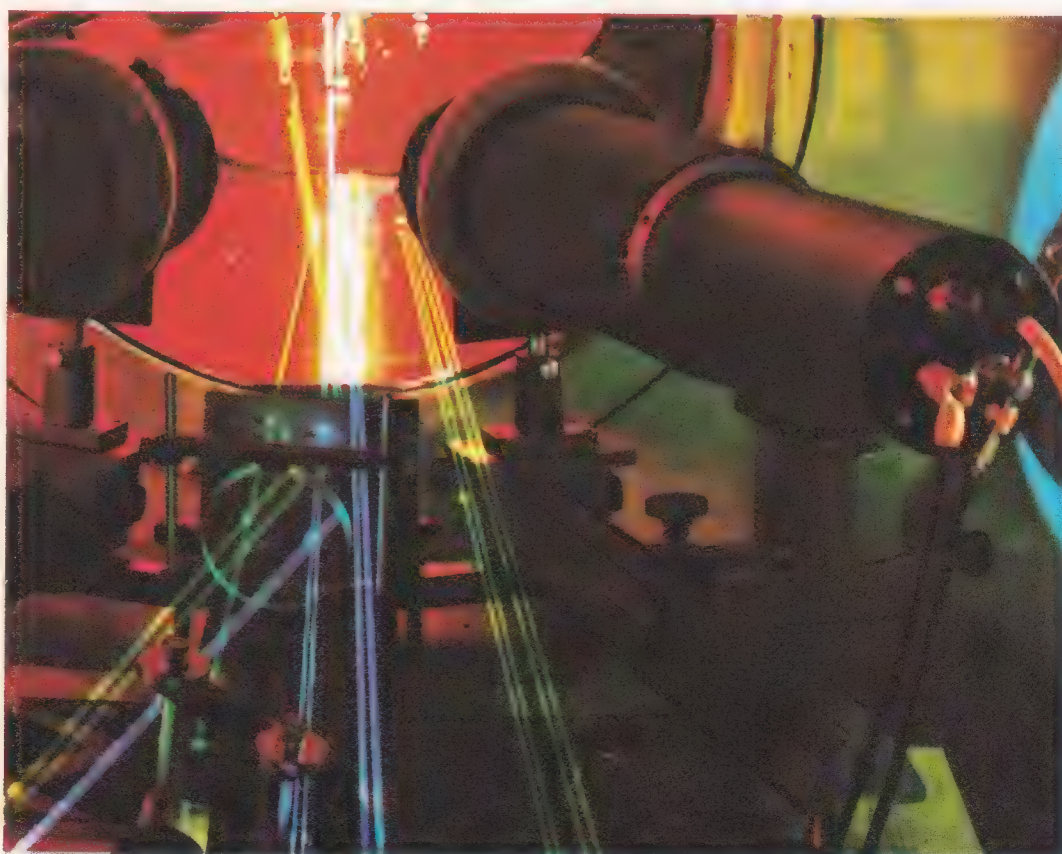
Holographic images can be made in colour, and it may one day be possible to have holographic television. Such a system could produce a totally life-like image that would occupy a corner of the room just as if it were real.

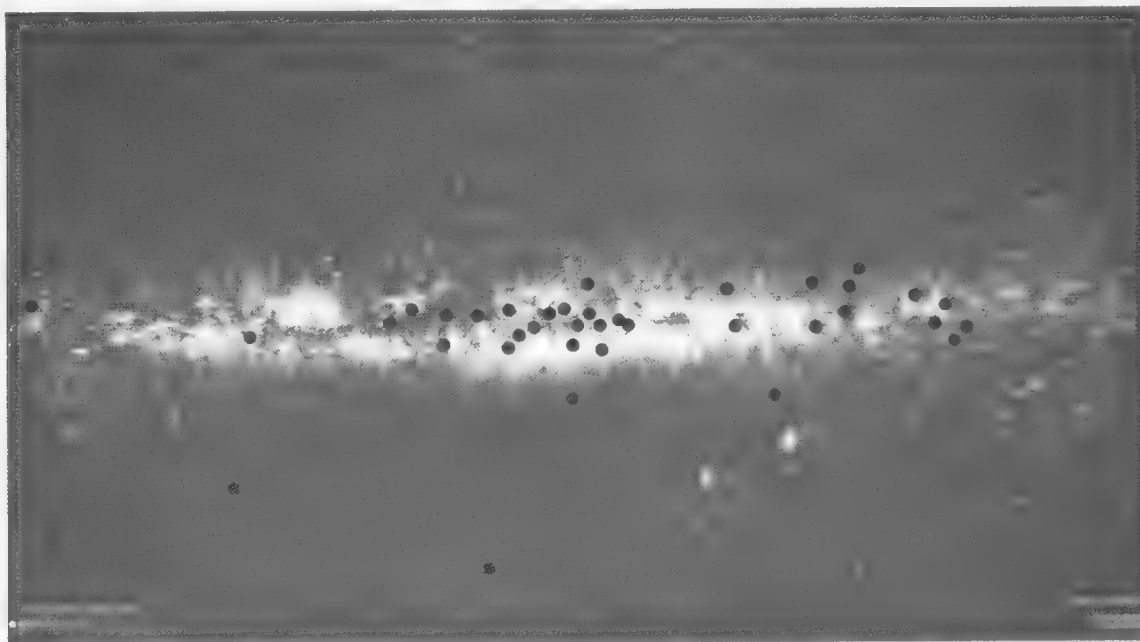
orbits by this action. Suddenly, an atom returns to its low-energy state and gives out light. This starts off a cascade of light production from all the other high-energy atoms. An intense pulse of light builds up and leaves one end of the laser. The light is amplified in this way, and it is done by stimulating the emission of radiation (light) from high-energy atoms with the light produced by the initial atom. This is why the laser is so named.

The beam produced is straight and very narrow, and can be used for precise alignment of tunnels and pipelines. It hardly spreads at all, reaching a width of only three kilometres at the distance of the Moon. Laser beams are fired at mirrors left by the Apollo astronauts to give a very accurate measure of the Moon's distance. A laser beam can also be modulated to carry information, rather as a radio wave is modulated (see page 104). Because of the higher frequency of laser light, it can carry vast amounts of information. On Earth, fog and mist would block the beam but for communications in space, the laser would be ideal.

A laser interferometer is an instrument for measuring minute distances by interference between two laser beams (see page 92). It can detect minute movements, such as those across geological faults and in dam walls. A laser gyroscope that has no moving parts but can detect changes of direction works in a similar way.

Nuclear energy may also benefit from the laser. Thermonuclear fusion could possibly be triggered off by laser beams, and laser light may also be used to produce nuclear fuel.





Left: A view of the Galaxy with known X-ray sources superimposed in black. These X-ray sources are detected by satellites.

Below: The arrangement of atoms within a crystal can be found by passing a beam of X-rays through any piece of crystal. The X-rays pass between the atoms but are diffracted (bent) as they do so, producing a pattern that can be recorded on a photographic plate. This photograph shows the X-ray pattern of DNA, whose structure was deduced from X-ray evidence.



X-rays

In the electromagnetic spectrum, waves with the smallest wavelength have the highest energy. Beyond the visible spectrum, beyond even the ultra-violet, is the region of penetrating, high-energy radiation, both man-made and natural. At 3×10^{-10} metres, X-rays are first encountered. By 3×10^{-12} metres, the X-rays are so 'hard', or penetrating, that they are designated γ -rays and become too dangerous for medical use.

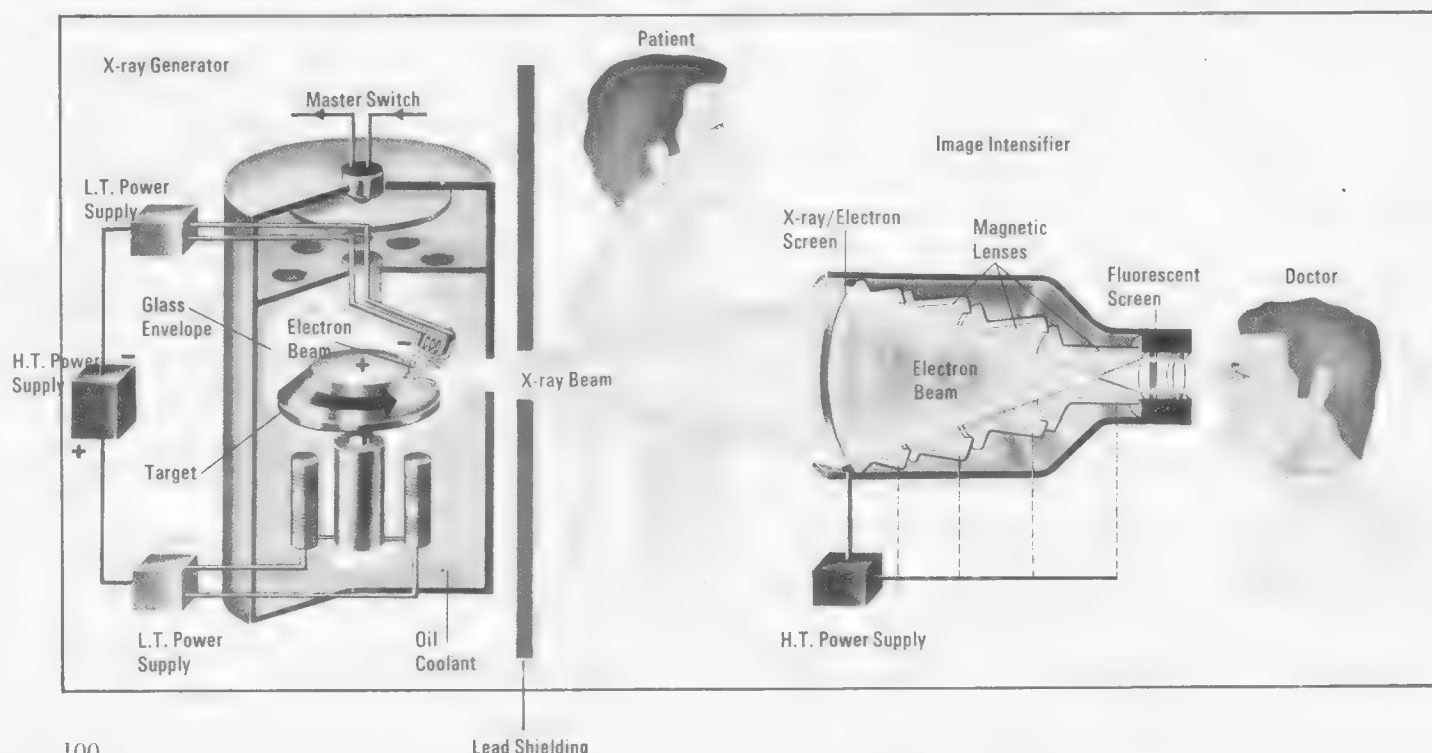
Both in the emissions from nuclear reactions and in cosmic radiation from outer space, shorter and shorter wavelengths are encountered. Some photons that originate in

the depths of space have wavelengths of 3×10^{-24} metres. These are therefore one hundred thousand billion times more energetic than visible radiation.

X-rays were first discovered by Röntgen in 1895. Within months they were being used to show up some lead pellets accidentally shot into a New York lawyer's hand. The principle of the medical X-ray photograph is as simple as a shadowgraph. Although X-rays pass through all human tissue, they are at least partially absorbed by the solid matter of the bones. These cast a partial 'shadow' which is made to fall upon a photographic plate.

The radiation is produced by causing fast-moving electrons to be stopped very rapidly. In the typical X-ray generator, electrons are boiled off from a heated cathode, accelerated through a high potential, and then stopped by means of a solid target. Often the target is

Below: An X-ray machine in use in a hospital. The X-ray beam passes through the patient's chest and strikes the screen of an image intensifier. The screen produces an electron beam that causes a picture to form on a fluorescent screen viewed by the doctor. The intensifier enables low doses of X-rays to be given.



made to rotate in order to dissipate heat. Fluorescent screens and image intensifiers are often used in place of the photographic plate. In this way the medical diagnosis can take place there and then.

X-rays may be used not merely in the diagnosis of illness, but to some extent, too, in the effecting of the cure. Cancer is a disease which affects the cells of the body. In the course of this illness, cells in certain locations grow rapidly and chaotically. The only cure that may be applied is the removal or else the killing of the rogue cancer cells. In this case, X-radiation is enormously useful, for in high concentration it will kill cancer cells.

Both X-rays and the more penetrating γ -rays are used to develop new strains of organisms useful to man. Bacteria in microbiological research, and crop-plants such as wheat are typical examples. Both have modified their form, or *mutated*, under the influence of radiation. The genetic blueprint material—the chromosomes and genes within every cell—can be shaken into new patterns by heavy doses of γ - and X-rays. The new genetic structures are generally disadvantageous. The resulting mutations, therefore, produce no improvements at all. Every once in a while, however, a genuine improvement does take place, as with the emergency of long-eared wheat or disease-resistant bees.

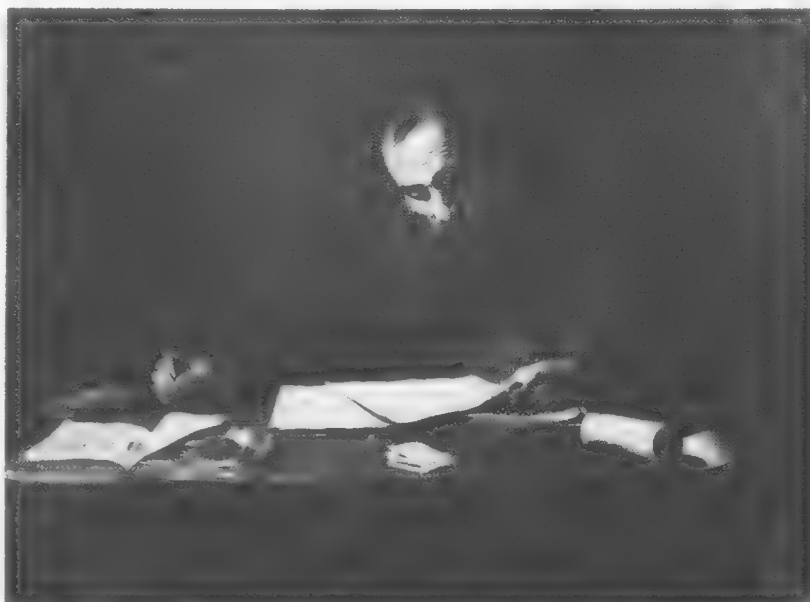
X-ray Diffraction

X-rays have been used to uncover the structure of matter. Since they are electromagnetic in nature, X-rays, like light, can be diffracted. However, owing to the extremely short X-wavelength, normal diffraction gratings cannot be used. Within the lattice of a crystal, however, the atoms are arranged into regular planes. These planes act exactly like the rulings in a grating and cause diffraction to take place.

By beaming X-rays onto crystals and then exposing a photographic plate to the emerging X-rays, a diffraction pattern is recorded. This pattern is specific both to the crystal and to the wavelength of the X-ray used. The unknown crystal structure of substances can be determined from such photographs. The reverse is also true. By means of the diffraction of *identified* crystals, the wavelength of the incident X-rays can be determined. This remains the most practical measurement technique for X-rays of unknown frequency.

X-ray diffraction has been used to identify totally new elements and a new science of X-ray spectroscopy has grown up following the lead of the physicist, Henry Moseley. Basic to this study is the fact that atomic number and X-ray spectra are directly related. Early in this century Moseley suggested improvements to the Periodic Table of elements. He went on to indicate that only seven missing elements existed between hydrogen and uranium at that time.

For very energetic γ -rays, the problem of artificial production is very great indeed.



Both X- and γ -rays are produced in great quantities by fission and fusion, and isotopes produced by these two processes remain one of the most widely accessible sources. High energy accelerators (atom smashers) are another useful source of isotopes. But radioactive isotopes are not always under our direct control. Fission and fusion bombs have released tons of such substances into the environment. γ - and X-induced radiation sickness continues to add to the toll of death and injury long after the explosions of these weapons.

In space, γ -radiation is intense and energetic. Cosmic rays (extremely short γ -radiation in the company of energetic nuclear fragments) emanate from the Sun, from the centre of our galaxy, and from interstellar space. Although these have proved a great danger to travellers in space, on the surface of the Earth, they have at last been put to good use. The penetrating power of cosmic rays has been used to survey such structures as the Great Pyramid of Cheops by a shadowgraph technique.

X-ray photography can show up hidden paintings. X-ray examination of St Paul in his Study (top) by the French painter Valentin (1594-1632) revealed that another picture lay beneath (above). The picture of St Paul had been painted over a picture of an artist at work on a portrait. Furthermore other figures, including an upside-down Christ under the painter's arm, appeared in the X-ray photograph. Such studies are invaluable to art historians.



Ultra-violet and Infra-red

Ultra-violet and infra-red radiations border on the visible spectrum. The two regions start at the farthest extent of the visible (violet at 4.0×10^{-7} metres; red at 7.6×10^{-7} metres), and extend towards the region of X-rays and that of radar and microwaves.

Ultra-violet Radiation

A considerable amount of ultra-violet radiation is present in the light from the Sun. Our bodies require this radiation in order to manufacture vitamin D, which protects us from the deficiency disease, rickets. Nevertheless, the radiation itself penetrates only a small way into the skin. This means that the biological action must be localized in the uppermost cells of the skin's epidermis. The bronzing and burning of the skin cultivated by sunbathers has both beneficial and harmful effects. At the same time as vitamin D is being manufactured, ultra-violet rays are destroying the upper cells and 'burning' the skin. Increased production of the brown pigment *melanin* prevents the ultra-violet radiation penetrating too far into the skin.

In spite of the evident sensitivity of the whole human body to ultra-violet light, it is nevertheless invisible to everyone except,

Above: Aerial photographs taken on infra-red film often show many details that are hidden on the ground. Here, an unsuspected archaeological site is revealed.

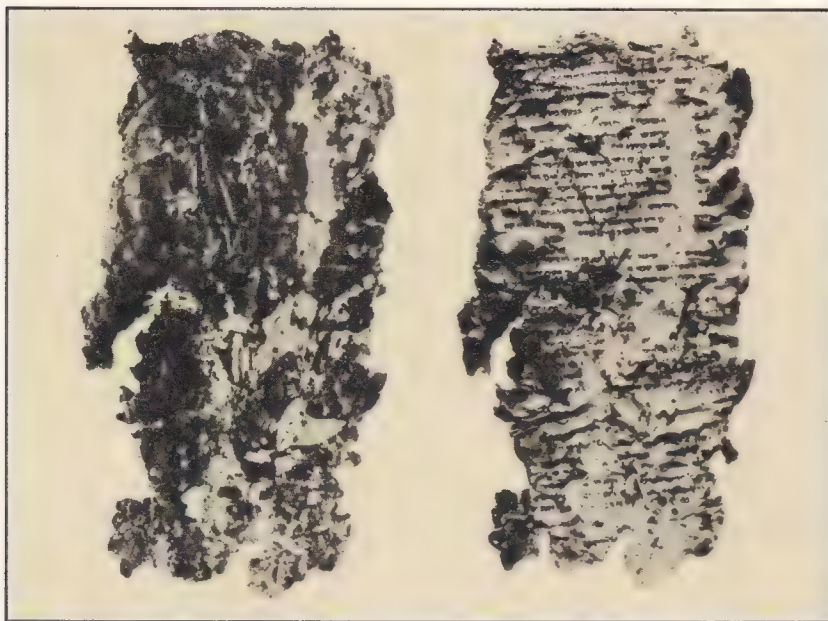
Right: A photograph taken in ordinary light shows a bust and two irons (top). The two irons provide infra-red light to illuminate the bust for an infra-red photograph (bottom). Note that one iron is hotter than the other.

perhaps, very young children. It is detected quite easily, however, by refined versions of the spectroscope. For such devices, glass lenses and prisms cannot be used since they are opaque to these wavelengths. Diffraction gratings take their place and photographic film sensitive to these radiations is easily manufactured. Other detectors are the photoconductive cell and the phototube. The former acts by changing its electrical conductivity in response to ultra-violet light. The phototube produces electrons in an extension of the photoelectric effect. The phototube receives ultra-violet light, photoelectrons are ejected from the cathode and are then multiplied many millions of times. Eventually these form a measurable electrical current by means of a series of high tension plates or *dynodes*.

Ultra-violet light is very strong above the Earth's atmosphere. It is, in fact, too strong for the well-being of terrestrial life. Fortunately, this radiation has a chemical effect upon the oxygen in the upper atmosphere. It causes oxygen molecules (O_2) to combine so that ozone molecules (O_3) result. This effectively acts as a barrier to most of the ultra-violet radiation. The amount that penetrates to the surface is not enough to be of harm to the organisms there, and to some species it is useful.

The chemical effect of ultra-violet radiation on oxygen is not unlike the phenomenon of fluorescence. Substances known as *phosphors* are able to absorb ultra-violet radiation and then re-emit the energy at a wavelength within the visible range of the spectrum. This effect is often quite dramatic. Since the ultra-violet light is invisible, the light emanating from the phosphor will be enhanced and





Above: The ancient writings known as the Dead Sea scrolls (left) only reveal their secrets in infra-red light (right). The ink has faded in ordinary light but still shows up in infra-red.

Right: Inspecting steel billets for surface cracks by ultra-violet light. This light shows as blue on colour film.

probably of a different colour. It will certainly appear as super-bright. Discotheque lights use this effect and, in addition, it is the basis of fluorescent strip lighting. It is also of great use in the field of forensic science.

Fluorescent substances are widely distributed. They are often present—to a varying extent—in substances such as inks. In this way the fraudulent addition of writing to, say, a document may be readily detected. In order to test for forgeries, all that is necessary is to examine each document under ultra-violet light. Slight differences in the phosphor content of apparently identical inks will then readily show up. If a forger does not ensure that his own product is identical to the original in all possible combinations of ultra-violet illumination, he may quickly be caught out in his crime.

Infra-red Radiation

Infra-red radiation is experienced by the human body in the form of radiant heat. Some 60 per cent of the Sun's total energy output is in this energy range. To a greater or lesser extent, all bodies emit infra-red radiation. Certainly, incandescent sources such as filament lamps emit rather too much of their energy in this form.

As with ultra-violet light, infra-red is used in medical practice in the treatment of strains, sprains, arthritis and muscle pain. Here the radiation's penetrating power is used to bring heat to a deep level in the muscle, well below the skin.

In chemical analysis, too, infra-red has proved to be of great use. It has given rise to its own particular technique, infra-red spectroscopy. Unlike the absorption lines in the

visible spectrum, the infra-red lines correspond to *molecular vibrations*. Whole groups of atoms—radicals as well as molecules—may be identified by observations of the absorbed infra-red wavelengths.

From space, infra-red photographs of the Earth's surface often show enormously useful information. Because infra-red film is able to distinguish minute surface temperature fluctuations, diseased crops may be surveyed instantly, and mixing ocean currents become evident at a glance. Such photographs are also able to show 'cool shadow spots' on the Earth. These areas occur whenever the Sun's direct rays are cut off in shade. The effect of the cool spot persists long after the shadow is removed. From space it is now possible to photograph not only where a truck is located at any given moment, but also to show conclusively where it has been parked, and perhaps for how long.



Radio Waves

Early in the nineteenth century, Michael Faraday showed that electric currents generate *magnetic* fields when they flow. Later, in 1864, James Clerk Maxwell proved mathematically that electrical disturbances produce effects *at a distance*. He showed that electromagnetic energy could move outwards in the form of waves, thereafter travelling at the speed of light. The way was thus opened for communication by radio.

Heinrich Hertz, in 1888, was the first to produce such an effect. He caused a spark to be triggered by radio emission from a larger more powerful spark discharge placed some small distance away. Guglielmo Marconi followed up these experiments in the firm belief

Below: A scene in a television studio. Microphones pick up the sound of the actor's voice and the cameras record the picture before them, turning sound and vision into electric signals. The signals are amplified and then fed to the transmitter.

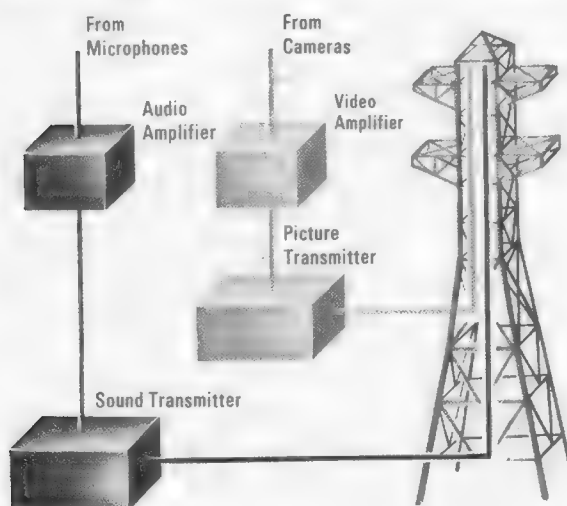


that electromagnetic waves could be used to transmit messages. He devised an apparatus in which the spark gap was connected between an elevated wire (in effect, an aerial), and the Earth. His receiver was placed at first only nine metres away. But gradually he moved it, with continued success, two hundred and seventy-five metres away, and finally to three kilometres. By 1901 he had not only bridged the English Channel, but even sent the morse letter 's' from Cornwall, England to Newfoundland, Canada.

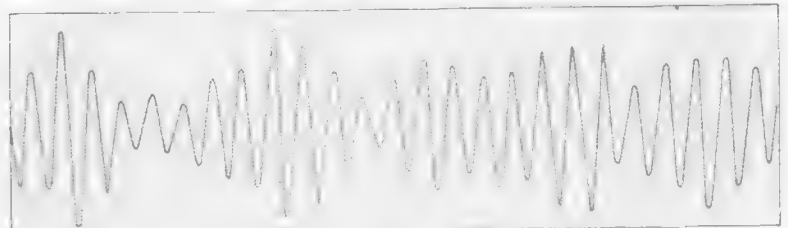
Nowadays, very complex radio signals are sent by modifying the uniform waves produced by an alternating electric current. In effect, the transmitter sends out a uniform radio signal and the electronics are arranged so that speech or television pictures are impressed upon the radio waves. The process of coding the (carrier) radio wave is known as *modulation*, and involves either altering the amplitude of the wave, or its frequency. Speech itself is represented by an irregular wave pattern and the transmitter is designed so that the carrier wave varies in frequency and so duplicates the pattern of the broadcast speech or music. This is known as *frequency modulation*.

At the receiver, electrons in the aerial vibrate sympathetically with the received radio wave. Thus the flow of electricity which they comprise forms an alternating current. The signal is then *amplified* by electronic means. The coded speech signal, too, must also be untangled from its carrier and this is achieved by a *demodulator*. Further amplifiers increase the strength of the reconstituted signal, so that ultimately it is strong enough to drive the coil of a loudspeaker and be converted into sound.

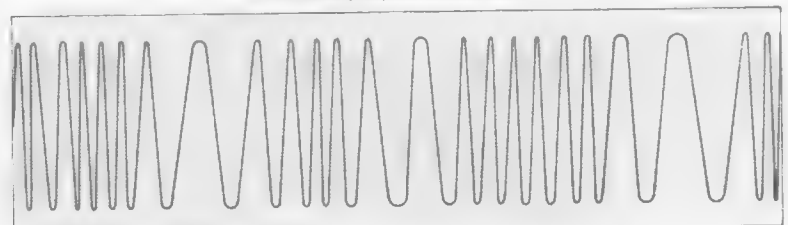
Below: At the transmitter, the signals are combined with radio waves known as carrier waves. The signals vary depending on the patterns of sound and light being transmitted, and these variations are impressed on two carrier waves by varying the amplitude of one (top) in step with the video (vision) signal and the frequency of the other (bottom) in step with the audio (sound) signal.



Video Wave (Amplitude-modulated)



Audio Wave (Frequency-modulated)



Television Broadcasting

Television pictures, too, may be sent via a carrier wave, but for this *amplitude modulation* must be used. The scene in the television studio is recorded by the camera, in which the scene appears as a series of lines. On each line the amount of darkness and light varies. Many times a second, the image in the camera is scanned by an electron beam. Dark and light parts of each strip return differing numbers of electrons. These are received by the transmitter and then amplified. The next step is to imprint the corresponding pattern upon the radio wave. For this, an ultra high frequency (UHF) carrier wave is used with a frequency in the range of 3×10^8 to 3×10^9 hertz (cycles per second).

The picture is encoded by varying the *amplitude* of the wave. Between certain pulses, the waveform is made to vary so that when high crests are transmitted, a corresponding 'dark spot' is indicated. When low crests are transmitted a corresponding 'bright spot' is indicated.

In the camera, the scanning beam moves across a horizontal line of the screen. At the receiver, a similar electron beam traverses the domestic television screen. As this moves along its path, it excites small phosphorescent spots. If the electron beam is intense it records a bright spot in the scene.

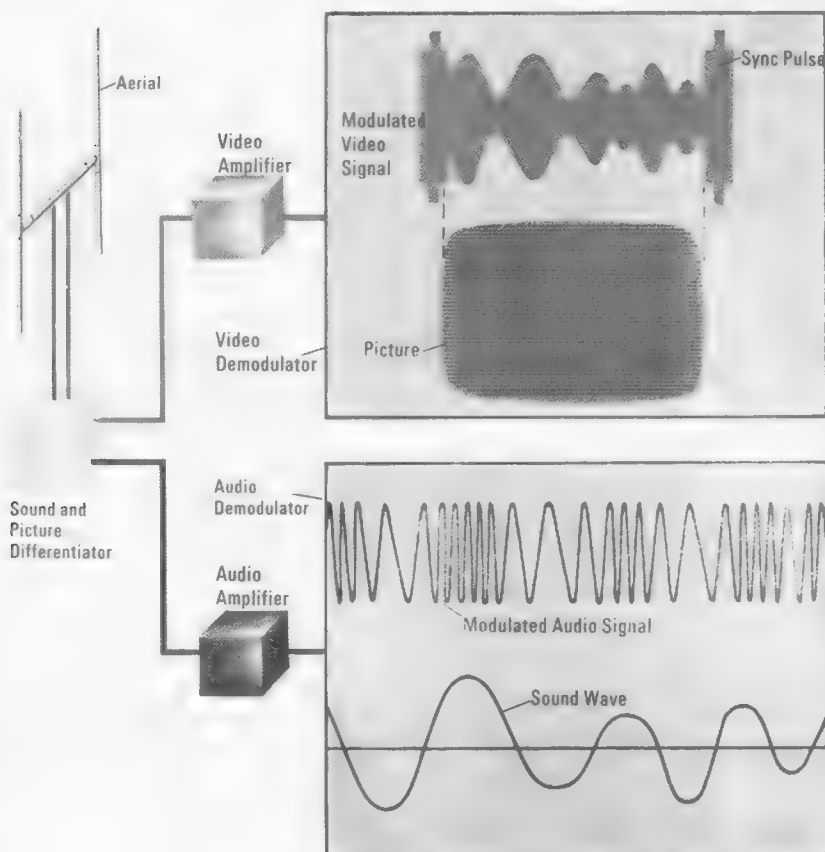
The timing for the scanning beams in studio camera and television receiver is kept strictly synchronized. The pulses mentioned earlier act as coded time signals. In terms of the waveform, these 'sync pulses' appear as regular square-topped peaks sent out by the

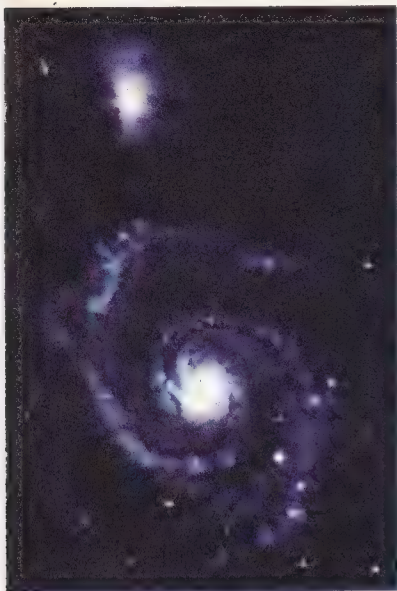
transmitter. Whenever one is received, the scanning beam is instructed to start another strip on the domestic screen. When it returns to the beginning it is moved fractionally lower as well. In this way it covers the whole television screen. Normally 625 such lines are involved in generating a UHF picture and the whole of the scene is covered more than thirty times each second.

Colour television also works on this principle, but it can be thought of as three such systems working in parallel. The camera in a colour television studio registers the brightness of points within the scene in terms of the three primary colours—red, green and blue. In practice, so as to accommodate black-and-white as well as colour receivers, the three are added together and a single 'brightness' signal is transmitted as before. Nevertheless, mixed in and on the same carrier wave, there is information about the 'redness', 'greenness', and 'blueness' of each spot of the scene. At the receiver screen, three different phosphorescent substances are used which will reproduce all the colours.

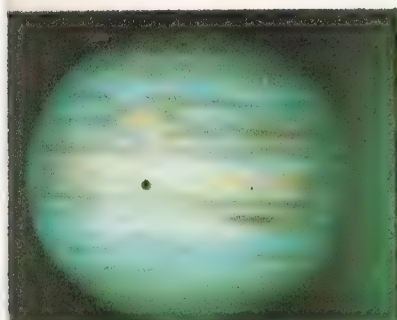
The frequency of the carrier wave for the transmission of the picture is necessarily higher than that for the speech channel. The reason for this is that more information is involved. However, owing to the large number of radio and television stations, it is necessary to allocate particular frequencies to each channel concerned. This necessitates the fitting of selector mechanisms (tuners) to all radio and television receivers. These allow unwanted station signals to be suppressed, and receivers to be tuned to a single channel.

Below: The carrier waves are received by the aerial at home. The aerial produces electric signals varying with the carrier waves, and these are separated into video and audio signals. They are then demodulated (the carrier waves are removed), leaving the original video and audio signals as produced by the cameras and microphones in the studio. These are fed to the tube and loudspeaker of the television set, which reproduce the picture and sound in the studio.





Above: A computer-plotted radio scan (right) of the Whirlpool galaxy (left) shows radio peaks that do not correspond to bright sources of light.

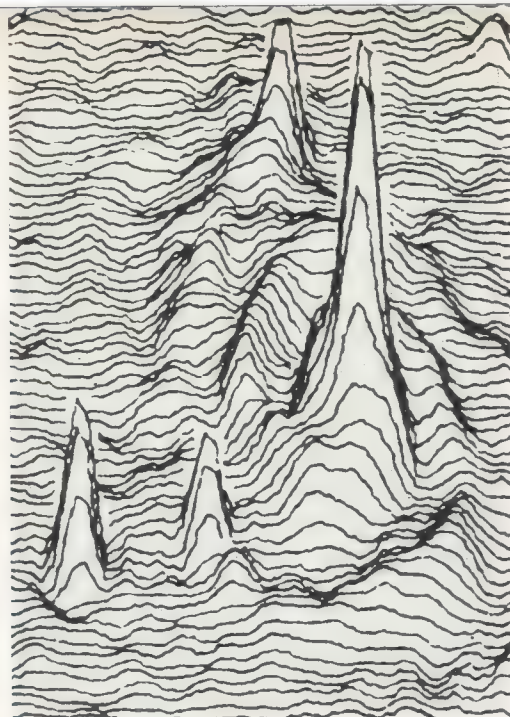


Above: The planet Jupiter is an intense source of radio waves, produced by the strong magnetic field that surrounds the planet.



Above: The British radio astronomer Sir Martin Ryle has pioneered the use of radio telescopes made up of long lines of aerials.

Right: Many radio telescopes have large dishes to capture radio signals from the heavens. The dish of this aerial at Effelsberg in West Germany is 100 metres across.



Radar

Radar owed its origins to the military demands of World War II. However, after the war the way was clear to develop its many non-military applications. In addition to this, scientists were able to apply the techniques of radar to related fields. They turned their attention to the ionosphere, to cosmic rays, and the study of the universe by means of radio-frequency electromagnetic waves.

Radar uses electromagnetic waves that have wavelengths of between 1 mm and 10 cm. Beyond this the radio wavelengths extend from *ultra high frequency* to *long wave* and beyond. (UHF: 10 cm and upwards. Long wave: around 3×10^6 metres.) This region is important to the science of radio astronomy.

The principle of radar is simple. Electromagnetic waves are generated using an oscillator. They are then transmitted via a specially designed movable antenna. On meeting an object, the radar wave is reflected, and part of the reflected beam is received by the original antenna. Because the speed of the radar wave is known precisely (the velocity of light), the time lag is an exact indication of the distance, or range, of the object. The radar wave is transmitted as a pulse. The delay

between the transmission and reception of a pulse is converted automatically into a measurement of distance and is displayed upon a cathode ray tube. In appearance this resembles a circular television screen. A spot in the centre represents the transmitter. As the antenna rotates, sending out and receiving pulses from all solid objects, a corresponding radius moves round the radar screen. This picks out the locations of every object in range.

The overall display has the appearance of a map, with aircraft, ships, and other objects set off against the features of the terrain. Such a facility is obviously of exceptional military value.

Reflected pulses from an approaching object are received at a higher frequency than that at which they were transmitted (*vice versa* if the object is receding). This has made radar particularly useful in the field of astronautics. Pulses from spacecraft approaching planetary surfaces (the Moon, Venus, Mars, Mercury and Jupiter to date) give highly accurate information. They indicate not only the distance from the body, but also the rate of approach. So precise are these measurements of distance, speed and acceleration, that it is possible for spacecraft to be docked automatically by radar contact alone.

Invisible Astronomy

In the wider universe, the study of the many very distant objects has been made possible by the recent development of the radio telescope. Radio emission in the heavens comes from a variety of sources. It can be investigated at various wavelengths by suitably 'tuning' the radio telescope. A general background radiation comes from the Milky Way; it is concentrated in Sagittarius, towards the centre of our galaxy. One variety of radio emission from the Milky Way is that of atomic hydrogen, which is found in considerable quantities between the stars. By studying this emission astronomers have been able to trace the spiral structure of our galaxy.

Many thousands of point sources of radio waves have also been mapped. Some are invisible, though others can be identified with objects visible through the optical telescope.

Listening In

Radio emission from the heavens is so feeble that radio telescopes have to be very large indeed. And even the largest ones have poor *resolving power*—the ability to distinguish between objects close together—compared with their optical counterparts.

The essential features of a radio telescope are a reflector to concentrate the incoming radio waves and an antenna, or aerial, placed at the point where the waves are concentrated. The feeble radio waves are amplified, and may then be translated into audible sounds or fed to a recorder which makes a trace of the emission pattern. Usually the signals go to a computer for analysis.



Electrons in Motion

A Van de Graaff generator is used to produce a high voltage. The bottom of the main column contains a set of spikes connected to an electricity supply of ten to fifty thousand volts. Electric charges are sprayed from the spikes on to a moving belt, and transferred to the dome at the top of the column (out of the picture). Here the charge can build up to several million volts. The dome of this generator has been connected to a steel ring, which is insulated from the ground. A steel girder placed near the ring causes the generator to discharge, and bright streams of 'lightning' flow between the ring and the girder.



The Nature of Electricity

Electrostatics

Electricity puzzled man for thousands of years. Not until the 1800s did he learn to harness it, control it, and make it do useful work. Around 600 B.C., the Greek philosopher Thales of Miletus found that rubbing a piece of amber with a cloth made it attract feathers and other light objects. This important discovery was the start of man's investigation of electricity—a word derived from *elektron*, the Greek for amber.

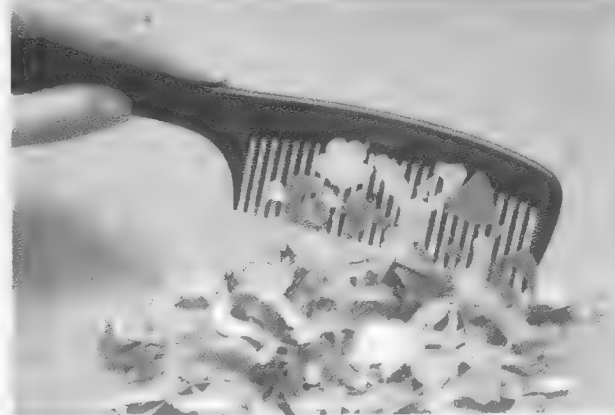
In the late 1500s, William Gilbert (1540–1603), physician to Queen Elizabeth I, discovered that rubbing glass, resin, or sulphur with a cloth made these substances attract light objects. By the 1650s, substances with this property were described as being electrified, or charged with electricity. We now call the study of objects charged in this way *electrostatics*. This is because the electricity in a charged body is stationary, or static, and can remain there indefinitely.

In 1733, the Frenchman Charles du Fay found that some charged objects attract each other, while others repel each other. Du Fay experimented further and summed up his results by stating that there were two kinds of electricity—*vitreous* (as in glass) and *resinous* (as in amber). Objects with different kinds of charge would attract each other, and objects with similar charges would repel each other.

Benjamin Franklin (1706–90) developed a theory that everything contains electricity, but the charge cannot normally be detected. Franklin maintained that a charge is apparent only when an object contains too much or too little electricity. He assumed that vitreous electricity was an excess of charge and, therefore, called it *positive* electricity. Resinous electricity, he said, was a deficiency of charge, so he called it *negative* electricity.

Franklin's idea that charged objects have either an excess or deficiency of electricity was correct. We now know that all matter is made up of atoms. Each atom consists of particles called neutrons (uncharged), protons (positively charged), and electrons (negatively charged). In an uncharged object, each atom has the same number of protons and electrons. Their opposite electrical charges cancel out, so that no overall charge can be detected. But, under certain conditions, an object can lose or gain electrons. When this happens, the electrical balance is upset, and a charge can be detected on the object. For example, when a piece of amber is rubbed with cloth, the friction transfers electrons from the cloth to the amber. The amber now has an excess of electrons (negative), giving it an overall negative charge. And the cloth, now having too few electrons to cancel all the positive charges of its protons, has an overall positive charge.

Similar effects occur with other materials. When an ebonite rod is rubbed with fur, the rod becomes negatively charged and the fur becomes positively charged. But rubbing a glass rod with silk produces the opposite effect. Electrons transfer from the glass to the silk, leaving the rod positively charged and the silk negatively charged.



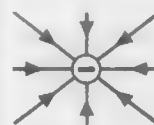
A comb that has been charged with static electricity will pick up small pieces of paper.

ELECTRIC FIELDS

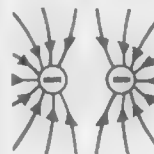
Near any charged object is a region in which the charge can be detected. This region is called an *electric field*. One way to detect the presence of a charge on an object is to place another charged object near it. The second object will tend to move away from the first object or to move towards it, depending on whether the two charges are like or unlike. By international agreement, scientists represent electrical fields by lines showing the direction in which a positive charge would move if placed in the fields. The lines are called lines of *electric force*. A single, positively charged body will repel another positive charge. The field around such a body is therefore represented by lines radiating from the body in all directions.



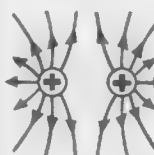
The electric field around a positively charged body.



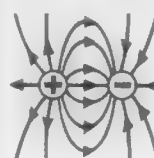
The electric field around a negatively charged body.



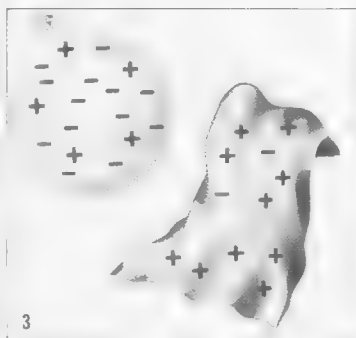
The electric field around two negative charges.



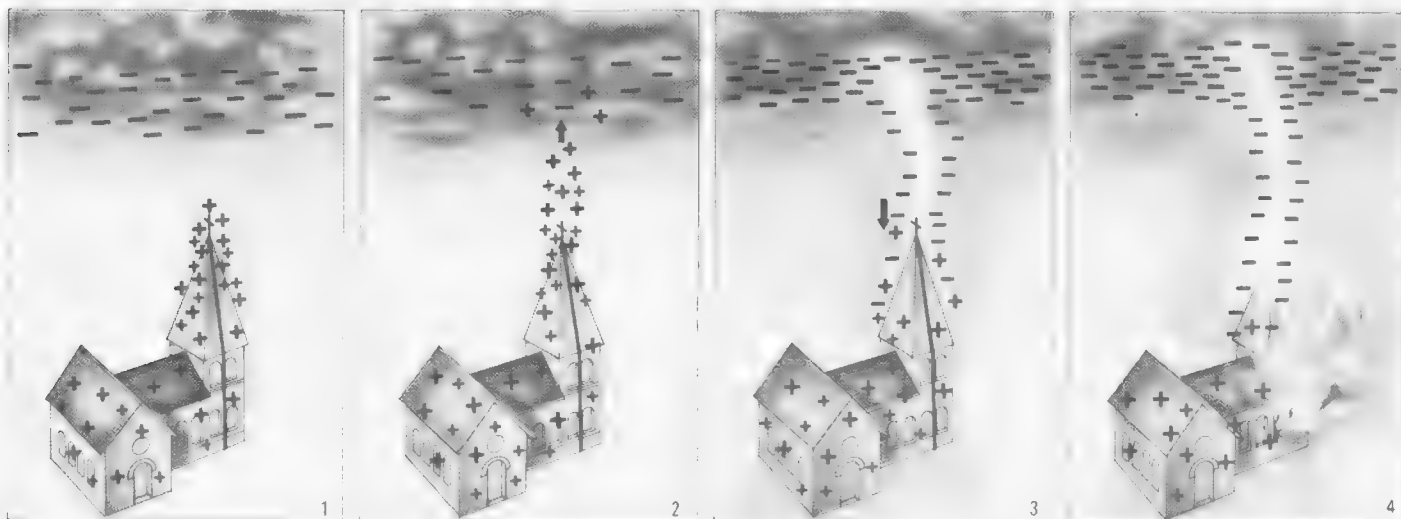
The electric field around two positive charges.



The electric field around two bodies with opposite electric charges.



1. An uncharged balloon and cloth each contain equal numbers of positive and negative charges.
2. When the balloon is rubbed with the cloth, electrons are transferred from the cloth to the balloon.
3. The balloon thus acquires an excess of electrons, and therefore has an overall negative charge. The cloth, having lost electrons, has an overall positive charge. The cloth and balloon will therefore attract each other. If two balloons are charged in this way, they will repel each other.



1. A lightning conductor consists of a pointed metal rod mounted on the roof of the building to be protected. The rod is connected by a wire to the ground. When a negatively charged cloud passes over the building, it repels the negative charges (electrons) in objects beneath it. The top of the building thus becomes deficient in electrons, and it acquires an overall positive charge. In any conductor, electric charges tend to pack tightly together at the most highly curved parts. For this reason, the pointed top of a lightning conductor acquires an extremely high positive charge. This charge ionizes the surrounding air — that is, it splits up the gas molecules of the air into charged particles. 2. The positively charged particles are then repelled from the point of the lightning conductor in a steady stream called an electric wind. The negatively charged cloud attracts these positive particles, which gradually cancel the cloud's charge, so that it eventually becomes electrically neutral. In most cases this prevents the building being struck by lightning. But, if the cloud has an extremely high charge, lightning may result. 3. If the building has a lightning conductor at its highest point, the lightning strikes this, and the charge flows safely down the wire to the ground. 4. When lightning strikes an unprotected building, the electric charge from the cloud passes through it, causing considerable damage.

Hair can be charged by combing with a plastic comb. The fine hairs on this boy's head all have the same charge, and therefore repel each other.



Insulators and Conductors

In 1729, Stephen Gray (1696–1736) discovered that it was impossible to charge any metal object held in the hand. From this he realized that electricity must be able to flow through metal and the human body. Charge could not build up on the object—it simply flowed away. But, if he mounted a metal object on a glass stand, Gray found that the metal could then be charged. The electricity could not flow away through the glass. Metals and other substances through which electricity passes easily became known as *conductors*. Glass, amber, ebonite, and other substances through which electricity cannot easily pass became known as *insulators*.

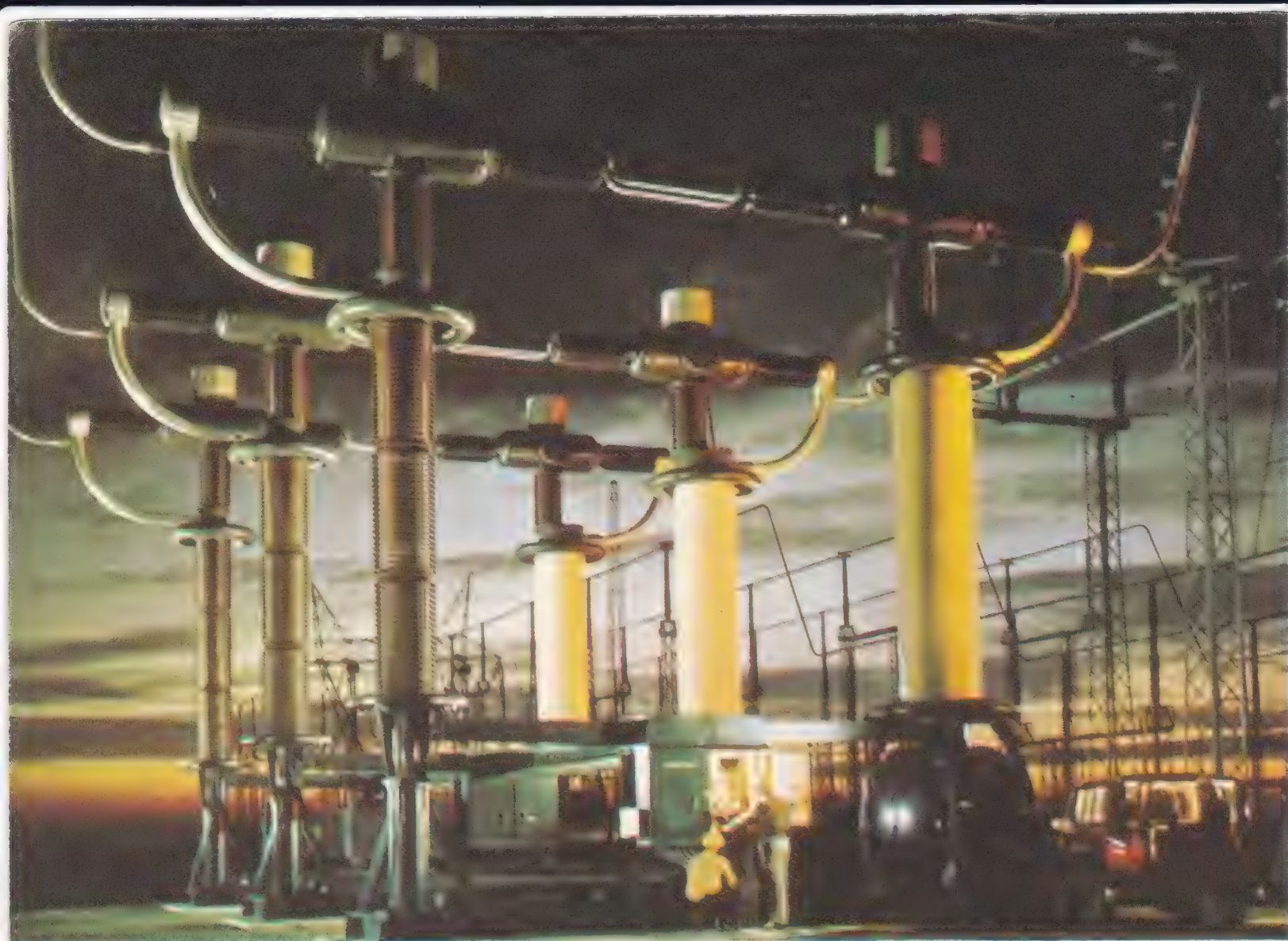
Shocks, Sparks, and Lightning

By the mid-1700s, several machines had been invented for producing electricity by friction. With these machines, it was possible to give objects extremely high electric charges, and it was soon found that electricity could cause painful shocks and produce brilliant sparks. The first electric machine was invented in Germany around 1600 by Otto von Guericke (1602–86). Turning a handle made a large sulphur sphere rotate. The sphere was charged by friction simply by resting a hand on it as it turned. Some later machines had an arrangement whereby the electricity produced could be stored in a conductor, insulated from the ground to prevent the charge escaping. If a person touched the charged conductor, he would feel a shock, and a spark would jump from the conductor to his hand as electricity passed through him. Scientists investigating these effects naturally employed assistants, many of whom were nearly electrocuted.

Benjamin Franklin observed the sparking caused by charged objects and suspected that lightning might be caused by electricity in the clouds. To investigate this theory, Franklin flew a kite carrying a metal rod during a thunderstorm. He tied the lower end of the kite string to a key and to a silk ribbon. Electricity passed from the kite, down the damp string to the key. Franklin held the silk ribbon, which was a good insulator, so that electricity could not escape from the key and it remained charged. On touching the key, Franklin felt a shock and saw sparks. This experiment, performed in 1752, showed that thunderclouds are electrically charged. Later experimenters showed that, even on a clear day, electricity could be collected from the atmosphere.

A few months after performing his kite experiment Franklin invented the lightning conductor—a simple, but extremely effective device for protecting buildings against lightning. From his experiments, Franklin realized that lightning occurs when the air below a charged cloud suddenly conducts the charge to the earth. The lightning conductor was designed to make clouds lose their charge slowly and safely, thus avoiding lightning. But, even when lightning does occur, the conductor serves to carry it safely to the ground without causing damage.

A negatively charged cloud produces lightning when the charge becomes too high. Electrons burst away from it and ionize a continuous path to the nearest point on the ground. The sudden discharge of electricity that results produces heat and light. We see the light as lightning, and the heat makes the air expand with explosive force to produce the sound of thunder.



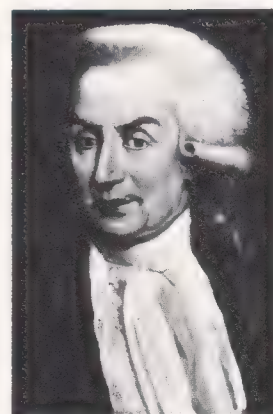
Electricity for use in the home and in industry is generated at power stations.

Sources of Electricity

Early experimenters used friction to generate electricity. By the late 1700s, scientists could produce extremely high charges in the laboratory. In 1786, while most scientists were shocking their assistants, the Italian Luigi Galvani (1737–98) experimented instead on dead frogs. He found that, like humans, they twitched when connected to an electric machine. Wishing to see whether lightning had the same effect, Galvani hooked some frogs' legs to the railings outside his house when a storm was approaching. To Galvani's surprise, he did not have to wait for the storm to come. The legs twitched each time they touched the railings. Galvani concluded, wrongly, that electricity from the frogs' nerves flowed through the hooks and railings and into the leg muscles, causing them to move as if they were alive. Electricity seemed to be the secret of life itself. This led other scientists to apply electricity to human corpses, hoping to restore life. In one experiment, electricity applied to a murderer, fresh from the gallows, made his legs kick, his face smile, and his lungs pump air. But no lasting effects

were achieved—death, after all, was permanent.

Meanwhile, the Italian scientist Alessandro Volta (1745–1827) had been pursuing another line of enquiry. In the 1790s, he discovered why the frogs' legs had twitched in Galvani's experiment. Volta found that electricity was produced when two different metals were connected by a moist conductor. Galvani had used brass hooks to suspend the frogs' legs (moist conductors) from iron railings. Each time the legs touched the railings, thus connecting the brass and iron, electricity was produced. Without knowing it, Galvani had made a form of electric cell—a device for producing a steady supply of electricity. Volta made a much more convenient and less messy cell using a pair of discs, one copper and one zinc, separated by moist paper or cloth. He then found that, by standing several of these cells in a pile, a stronger supply of electricity was obtained. And, if the paper separators were dampened with a solution of salt or acid, the strength of the supply was further increased, and a mild shock could be



Luigi Galvani (1737–1798) was born in Bologna. He later studied and practised medicine there. As a result of his experiments he thought he had discovered that electricity could be obtained from the body of an animal. He was wrong; he had in fact discovered the electric cell.

felt when the top and bottom discs were touched. Volta had invented the first battery, or assembly of electric cells. It became known as the *voltaic pile*.

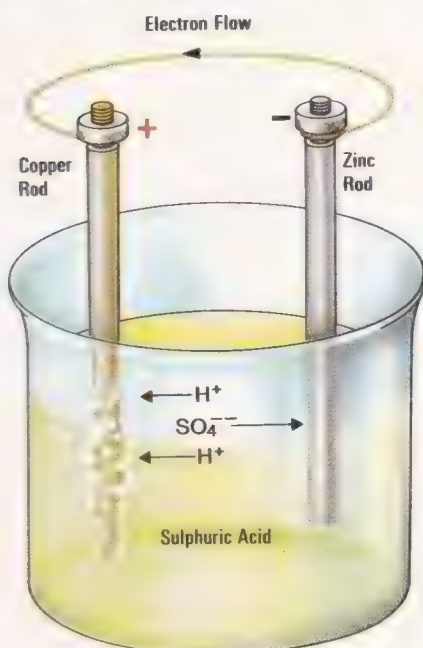
The invention of the cell was extremely important in the investigation of electricity and its effects. For, unlike an object charged from a friction machine, the cell provided an almost steady supply of electricity.

Current and Electromotive Force

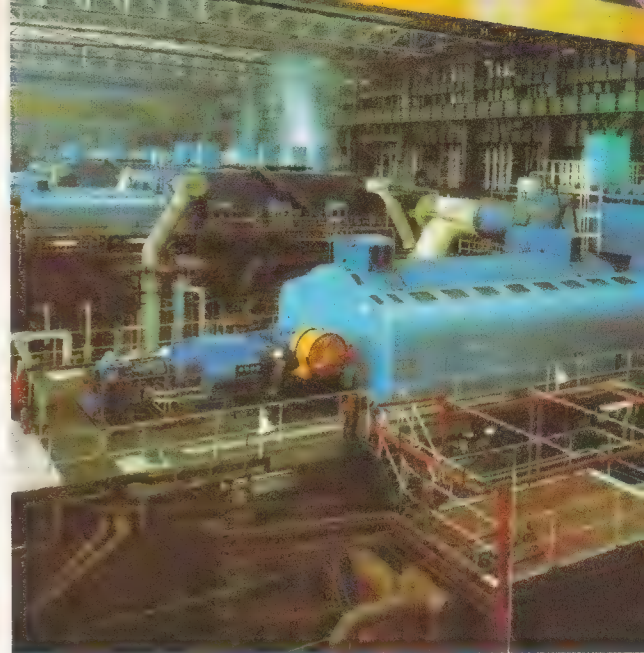
As electricity was originally thought of as an invisible fluid, its movement became known as a *current*. And any source of electricity was said to have an *electromotive force*—a force that made electricity move. Current is measured in units called *amperes*, and electromotive force (e.m.f.) is measured in units called *volts*. Whenever a wire or other conductor is connected between the terminals of a source of electricity, the e.m.f. will make a current flow around the circuit, or loop, formed by the source and the conductor. The current strength depends on the strength of the e.m.f. and the *resistance*, or opposition, of the circuit to the flow of current through it (see page 116).

Primary Cells

Following Volta's invention of the first practical electric cell, many other cells that worked on similar principles were developed. These are all now known as *primary cells*. In the *simple cell*, one of the earliest primary cells, copper and zinc rods dip in a dilute sulphuric acid solution. When the rods are connected together by a wire, a current flows around the circuit, and bubbles of gas form on the copper rod. This happens because, in solution, a sulphuric acid molecule (H_2SO_4) splits up into two positively charged hydrogen ions (H^+ , H^+) and a negatively charged sulphate ion (SO_4^{2-}). The two-minus sign shows that the sulphate ion has a surplus of two electrons (negative charges), giving it an overall negative charge. And the positive signs



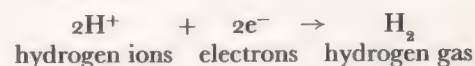
Right: The turbine hall of a coal-fired power station that produces 2000 million watts. The heat energy obtained by burning the coal is converted into electrical energy by the generators.



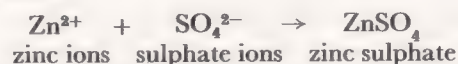
Above: The voltaic pile was invented by Alessandro Volta. He found that a layer of salt impregnated cloth, sandwiched between a piece of zinc and a piece of copper, produced an electric current. Several of these cells in a pile produced an even stronger current. The voltaic pile was the first battery.

show that the hydrogen ions have a deficiency of one electron, giving them an overall positive charge.

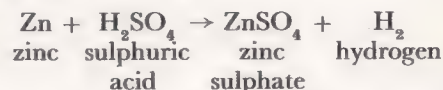
Zinc is strongly electropositive (see page 177), and some positive zinc ions (Zn^{2+}) leave the rod and enter the solution. Zinc ions are positive because they have a deficiency of two electrons. These missing electrons remain on the zinc rod, giving it a slight negative charge. Only a few zinc ions can leave the rod because the negative charge on the rod tends to attract the positively charged ions. But, when the rods are connected together by a wire, electrons from the zinc rod move along the wire to the copper rod. There, they attract the positive hydrogen ions from the solution to form hydrogen gas:



A continuous stream of zinc ions, no longer held by the attraction of electrons on the rod, now enters the solution. There the zinc ions combine with sulphate ions to form zinc sulphate:



The zinc sulphate formed dissolves immediately in the water of the acid solution. The whole process can be summed up by the chemical equation:



This reaction continues while the two rods are connected together, and electrons flow along the wire from the zinc rod to the copper rod. The zinc rod, being a source of electrons, is called the negative pole, or electrode, of the cell. The copper rod is the positive pole, or electrode.

In the simple cell, ordinary commercial zinc must not be used as it contains particles of iron as an impurity. The iron and zinc, being immersed in acid, would form numerous tiny cells on the rod. Electrons would flow from the zinc to the iron, and zinc would be

Left: A simple cell consists of two electrodes (one zinc and the other copper) immersed in a solution of sulphuric acid, and connected by a conducting wire. The sulphuric acid ionizes into hydrogen (H^+) ions and sulphate (SO_4^{2-}) ions. Zinc ions (Zn^{2+}) enter the solution from the zinc electrode, leaving it with an excess of electrons. The excess electrons flow round the wire to the copper electrode, which thus acquires a negative charge. This attracts the hydrogen ions, which form hydrogen gas on the copper electrode.

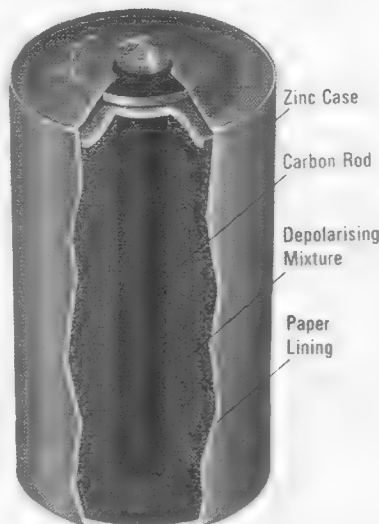
PRIMARY CELLS

The Daniell Cell

The defect of polarization was first successfully avoided in a simple cell invented in 1836 by John Daniell (1790–1845), professor of chemistry at Kings College, London. The Daniell cell has a zinc negative pole resting in a solution of dilute sulphuric acid contained in a porous pot. The pot and a copper positive pole are placed in a solution of dilute copper(II) sulphate. When the poles are connected by a wire or other conductor, a current flows through it. As in the simple cell, sulphate ions from the acid drift to the zinc rod. There they give up electrons and combine with zinc to form zinc sulphate. The hydrogen ions from the acid drift towards the copper rod. But, on meeting the copper(II) sulphate solution, the hydrogen ions remain in solution, while copper(II) ions move to the copper rod. Thus, no free hydrogen gas is released, copper being deposited on the copper rod instead. Polarization is, therefore, eliminated, so the Daniell cell can provide a useful current for much longer periods than the simple cell. The copper(II) sulphate solution, used to prevent depolarization, is called the *depolarizer*.

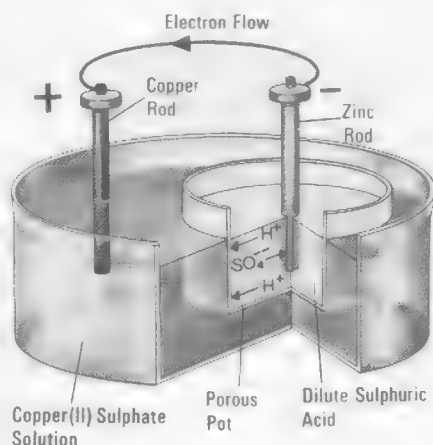
The Dry Cell

The dry cells used in flashlights today are direct descendants of the Leclanché cell, incorporating many improvements developed over the years. Inside the zinc casing, which acts as the negative pole, is a layer of absorbent paper wetted with the electrolyte



Above: A dry cell

ammonium chloride solution. Within this layer is a pasty mixture of manganese(IV) oxide, carbon, ammonium chloride, and zinc chloride. And in the centre of the cell is a carbon rod, which acts as the positive pole. Although this cell is not really dry, its liquid content in the paste and paper cannot be poured out. Also, the cell is sealed to prevent loss of liquid by evaporation. This makes the dry cell, unlike the Leclanché cell, convenient for use in portable equipment. Another advantage of the dry cell is that it suffers only slightly from polarization. It can, therefore, be used for long periods with only a slight decrease in the current it supplies.

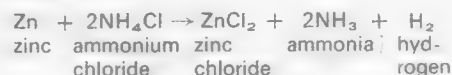


Left: A Daniell cell

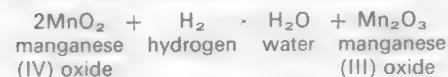
Right: A Leclanché cell

The Leclanché Cell

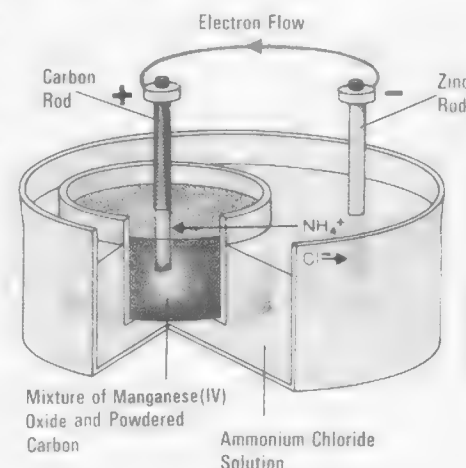
In 1866, Georges Leclanché (1839–1892) invented a cell that used manganese(IV) oxide as a depolarizer. In one form of this cell, a porous pot contains a carbon positive rod surrounded by a mixture of manganese(IV) oxide and powdered carbon. The carbon decreases the electrical resistance of the cell, enabling it to deliver a relatively high current. The porous pot and a zinc negative rod are placed in a jar of ammonium chloride solution. When the rods are connected together with a wire, electrons flow along the wire from the zinc rod to the carbon rod. At the same time, the following chemical reactions take place in the cell:



The hydrogen produced is attracted towards the carbon rod, but reacts with the surrounding manganese(IV) oxide to form water:



As the hydrogen reacts to form water, polarization is avoided. Unfortunately, if the cell is used continuously, the depolarizer cannot deal with all the hydrogen produced. So polarization occurs, and the current supplied by the cell drops rapidly.



used up to form zinc sulphate. This effect is called *local action*. If it is allowed to occur, the zinc plate will be eaten away, even when no conductor is connected between its terminals. To prevent local action, the zinc must be pure, or the plate surface must be amalgamated with mercury.

A great disadvantage of the simple cell is that, after a short time in use, a layer of hydrogen bubbles adheres to the copper rod. This effect, called *polarization*, increases the resistance of the cell and prevents it from working properly. Also, the hydrogen and zinc set up an e.m.f. that opposes the e.m.f. between the copper and zinc. This reduces the e.m.f. of the cell.

Improved primary cells were invented by John Daniell and Georges Leclanché. Nowadays the primary cell in common use is the dry cell, or battery.

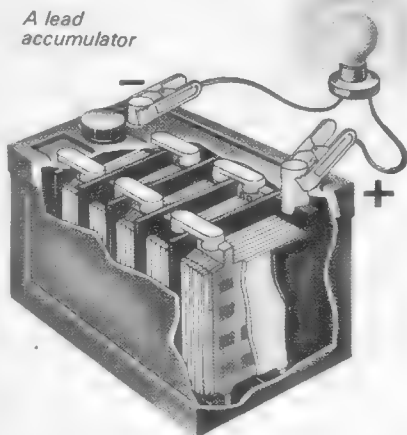
Secondary Cells

Drawing a current from a cell causes chemical changes to take place, and chemical energy is converted into electrical energy. As the original chemicals in the cell are used up, the cell 'runs down' and eventually becomes too weak to supply a useful current. In a primary cell, nothing can be done to change this state—the cell is useless. But another type of cell, called a secondary cell, accumulator, or storage cell, can be recharged with electricity when it has run down. By connecting a suitable electricity supply to the terminals of the cell, the chemical changes that take place when the cell is in use can be reversed. When the cell has been recharged, it contains exactly the same chemicals as it did originally. A carefully maintained secondary cell, therefore, has an almost indefinite life. A form of secondary cell in common use is the lead-acid cell.

Alessandro Volta (1745–1827) was born at Como in Italy. He continued the work of Galvani and showed that 'animal electricity' was the same as that produced by non-living objects. He invented the first battery — the voltaic pile.

SECONDARY CELLS

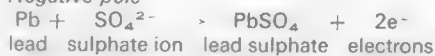
A lead accumulator



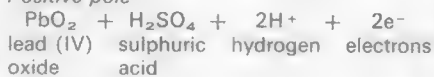
The Lead-Acid Cell

Most car batteries consist of six lead-acid secondary cells connected in series. When fully charged, each cell has an e.m.f. of about 2 volts, so the e.m.f. of the battery is about 12 volts. The lead-acid cell has a negative pole of lead and a positive pole of lead(IV) oxide in a solution of dilute sulphuric acid. When a conductor is connected between the two poles, sulphate(VI) ions from the acid give up electrons at the negative lead pole. The released electrons flow through the conductor to the positive pole. There, they neutralize the positive hydrogen ions from the acid. The neutralized sulphate(VI) and hydrogen ions undergo the following chemical reactions at the poles of the cell.

Negative pole



Positive pole

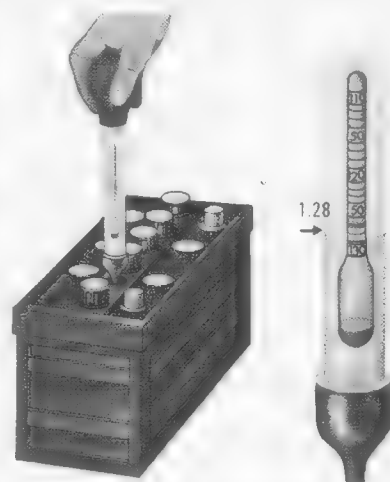
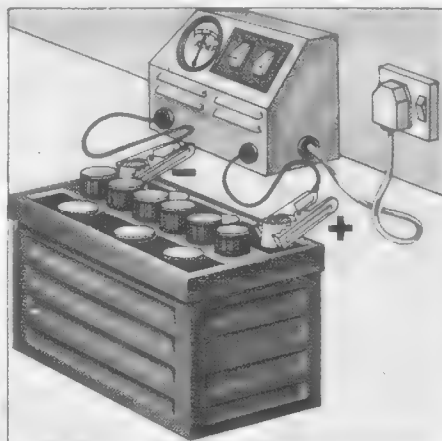
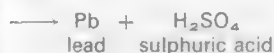
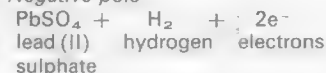


The lead(II) sulphate formed when current is drawn from a lead-acid cell gradually coats the two poles. If the coating is allowed to become too thick, it may be impossible to recharge the cell. In practice, a lead-acid cell or battery should be recharged whenever its

e.m.f. drops 10 per cent below the e.m.f. when fully charged. But, instead of checking the e.m.f., it is usually easier to check the relative density of the acid solution with a special hydrometer. The relative density of the solution is originally about 1.28. The water formed when the cell is in use gradually reduces the relative density. When it reaches about 1.17, the cell should be recharged.

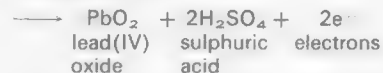
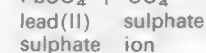
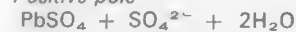
To recharge any secondary cell, electrons must be forced to move through a circuit from the positive pole of the cell to the negative pole—the opposite direction to the flow that occurs when the cell is supplying a current. This forced electron flow will reverse the reactions that have taken place in the cell and restore the original chemicals. To force the electrons to move in the required direction, an e.m.f. from another source is applied to the cell. Since the applied e.m.f. and the e.m.f. of the cell are trying to move the electrons in opposite directions, the applied e.m.f. must be the greater for recharging to take place. During recharging, hydrogen and sulphate(VI) ions in the acid solution lose their charges at the poles of the cell and then undergo the following reactions:

Negative pole



The relative density of a lead accumulator is tested using a hydrometer. A fully charged accumulator should have a relative density of between 1.20 and 1.30.

Positive pole



The net result is that the lead sulphate deposit is removed from both poles of the cell, the water produced during discharge is used up, and the acid used up during discharge is restored. This action is an example of *electrolysis*—the use of electricity to bring about chemical changes.

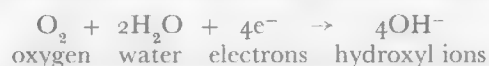
The Nickel-Cadmium Cell

The nickel-cadmium cell is used in some electric razors, flashguns, and other devices. The cell has an electrolyte of potassium hydroxide, a positive pole of nickel hydroxide and nickel oxide, and a negative pole of cadmium. Many devices powered by nickel-cadmium cells have a built-in charging unit. This is connected to the mains supply for a few hours when the cells need recharging.

Recharging a lead accumulator

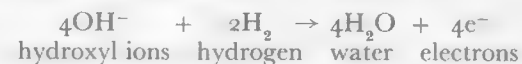
Fuel Cells

Fuel cells work on the reverse principle to *electrolysis*. In the electrolysis of water, for example, electricity is used to convert water into hydrogen and oxygen gases. One type of fuel cell produces electricity by the reverse of this process—combining hydrogen and oxygen to form water. The gases are forced at high pressure through electrodes consisting of perforated nickel plates into hot, concentrated potassium hydroxide solution. When the oxygen passes through its electrode and enters the solution, it combines with water to form hydroxyl ions (OH^-). In doing this, the oxygen removes electrons from the electrode. The reaction is represented by the equation:



The hydroxyl ions travel through the solution

to the other electrode, where they combine with hydrogen to form water. In this reaction, electrons are given up to the electrode:



The electrode through which the hydrogen passes is, therefore, negatively charged, since it has a surplus of electrons. These electrons will flow through a conductor to the other electrode which, being deficient in electrons, is positive. The current will continue to flow as long as hydrogen and oxygen are supplied to the cell. The potassium hydroxide solution, which provides a suitable path between the two electrodes, undergoes no permanent chemical change. But the water formed in the reaction must be removed, otherwise it will dilute the hydroxide and reduce the efficiency of the cell. Some hydrogen-oxygen



fuel cells have an acid electrolyte instead of the alkaline potassium hydroxide solution.

Fuel cells are currently used to power some military equipment and spacecraft electronic systems. At present, fuel cells are too costly for general use. Current research is aimed at producing a cheap and efficient cell that will operate efficiently on cheap fuel. When such a cell is developed, it will be used to power electric cars and other vehicles, which have an extremely limited range when powered with conventional batteries.

Mechanical Energy into Electricity

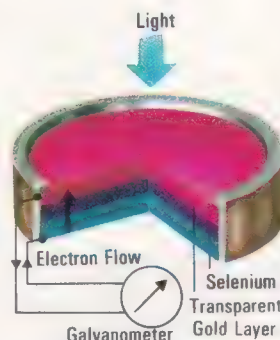
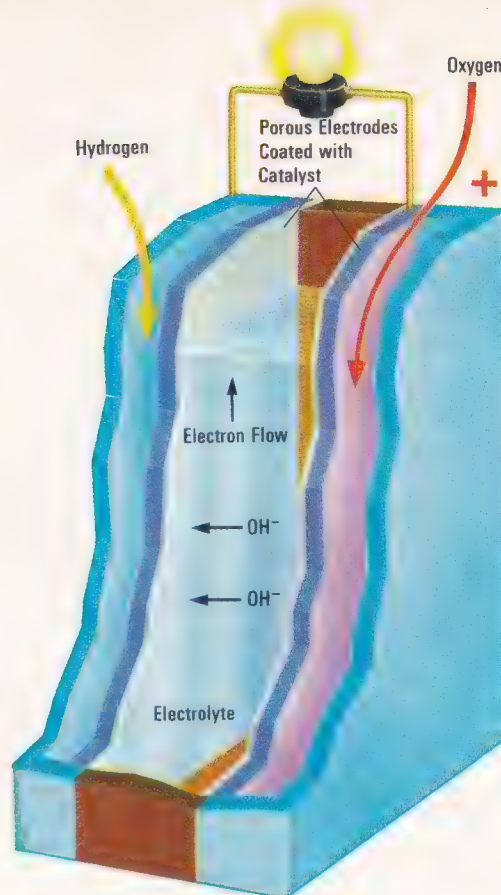
All sources of electricity are energy converters. The cells described earlier all convert chemical energy into electrical energy. Many sources work by converting energy of motion—mechanical energy—into electricity. In early electrical generators, for example, friction produced a charge on a rotating sphere or disc. Some of the energy used to turn the machine and overcome the friction was converted into electricity. Modern generators, from the bicycle dynamo to the huge alternators at power stations, use the principles of *electromagnetism* to convert mechanical energy into electricity (see page 118). Some microphones, such as the ribbon and moving-coil types, use the same principle to convert the mechanical energy of sound waves into tiny electrical signals (see page 120). In the crystal microphone, a slice of crystalline Rochelle salt (potassium sodium tartrate) converts mechanical energy into electricity by the *piezoelectric effect*.

Light into Electricity

Under certain conditions, light can cause a substance to lose electrons. In this process, called the *photoelectric effect*, some of the light

The simplest type of fuel cell uses hydrogen and oxygen. The fuels diffuse through the porous electrodes into the electrolyte. Hydroxyl ions (OH^-) are formed at the oxygen electrode, and these are attracted to the hydrogen electrode. This leaves the oxygen electrode with a positive charge, and gives the hydrogen electrode a negative charge. Electrons therefore flow round the circuit.

Below: A selenium photoelectric cell produces electricity from light. When light passes through the transparent gold layer and falls on the selenium, electrons are released. These flow around the circuit. The deflection of the meter needle depends on the intensity of the light falling on the cell. This arrangement is used in the photographer's light meter.

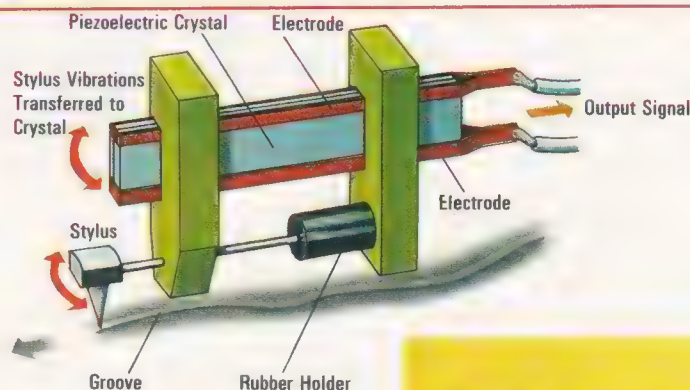


energy is converted into electricity. This is the principle of some photoelectric cells. In the selenium cell, for example, a disc of selenium is covered with a layer of gold, so thin that it is transparent. Light passes through the gold and strikes the selenium, causing it to release electrons. These pass into the gold layer, and will flow through a conductor connecting the gold to the selenium. Some light meters used by photographers are fitted with this kind of cell. Light from the scene to be photographed is allowed to fall on the cell, which is connected

THE PIEZOELECTRIC EFFECT

When pressure is applied to a crystal of Rochelle salt, an electric charge appears across the crystal. This is called the *piezoelectric effect*, and is exhibited also by some other crystals, including quartz. The effect can be demonstrated by connecting a sensitive meter to two metal plates clamped to a slice of piezoelectrical crystal. If a force is applied to the crystal, causing it to bend, the needle of the meter will deflect momentarily, showing that electricity has been generated. The greater the force applied to the crystal, the greater will be the charge produced on it. In the crystal microphone, energy from the sound waves picked up vibrates a piezoelectric crystal. The charge produced on the crystal varies in accordance with the pressure variations in the sound waves. The crystal thus generates an electrical signal that is an almost exact copy of the sound waves.

In the *reverse piezoelectric effect*, a varying electric signal applied to a crystal causes corresponding vibrations.



The pickup of a record player contains a piezoelectric crystal. Vibrations from the needle in the record groove cause the crystal to vibrate. This generates an electric current, which is then passed to an amplifier.



A generator produces electricity from mechanical energy. This is done using the principles of electromagnetism. A coil, or assembly of coils, are made to rotate in a magnetic field. If the coil forms part of a circuit, an electric current is induced to flow.



to a meter that measures current. The brightness of the light determines the current produced by the cell and, hence, the meter deflection. The meter can, therefore, be calibrated in light values or in appropriate camera settings.

Artificial satellites use photoelectric cells to convert sunlight into electricity for powering electronic equipment on board. The cells are connected together to form *solar batteries*.

Photoelectric cells that produce an e.m.f. are called *photovoltaic cells*. This distinguishes them from *photoconductive cells*, whose resistance is determined by the brightness of the light falling on them.

Heat into Electricity

If wires of two different metals are joined together and the junction is heated, an e.m.f. is produced. The heat causes electrons to transfer across the junction from one metal to the other, and these electrons will flow through a conductor connecting the other ends of the two wires. This effect, whereby heat is converted into electricity is called the *thermoelectric effect*, or *Seebeck effect*. It is used in the *thermocouple*, a device for measuring temperature. In this case, the cool ends of the pair of dissimilar wires are connected to a sensitive meter that measures current. The temperature of the junction of the two wires determines the current flow around the circuit and, hence, the meter reading. The meter thus gives an indication of temperature and can be calibrated with a suitable temperature scale.

A *thermopile* is a battery of thermocouples. Several thermocouples are connected in series so that their e.m.f.s are added together. The thermopile is, therefore, an extremely sensitive device. It gives a noticeable change in current for a very small temperature change.

Right: Skylab, one of the man-made satellites that orbits the Earth, uses photoelectric cells in its solar panel. The electricity thus made is stored in batteries, and then used to power Skylab's instruments.



Right: A thermocouple being used to measure the temperature of the pile cap in a nuclear reactor. A thermocouple generates electricity from heat. It consists of two unlike metals joined together in a circuit. When the metals are warmed, a current flows. This deflects the needle of a galvanometer calibrated to give temperature readings.



d.c. Circuits

When a torch is switched on, an electric circuit—a path through which an electric current can flow—is completed, or made. The current flows around the circuit, which includes the fine metal filament of the bulb, causing it to heat up and glow brightly. As the current always flows in the same direction, it is called direct current (d.c.). This distinguishes it from alternating current (a.c.), which continually reverses its direction of flow (see page 126).

All cells give rise to a direct current when their terminals are connected by a conductor of electricity. The current consists of electrons, which flow from the negative pole of the cell, through the conductor, and into the positive pole of the cell. A flow of 6.28 million million electrons per second is equal to a current of one ampere.

Benjamin Franklin did not know about electrons. But he did know that there were two types of electric charge. He called these positive and negative, and proposed that current would always flow from a positively charged object to a negatively charged object. Franklin pointed out that, in reality, current might always flow in the opposite direction to the one he had chosen. It was impossible at that time (the mid-1700s) to find out the true direction of current flow. But it was convenient for scientists, when exchanging ideas about electricity, for them all to mean the same thing by 'a flow of current'. So the direction proposed by Franklin—from positive to negative—became the *conventional* idea of current flow.

Many rules and theories involving electricity and magnetism were worked out on the assumption that electricity flowed in the conventional direction. This is now known to be the wrong direction, but it is still normal practice to show current flowing this way. Only in diagrams where the actual drift of electrons is important to the point being illustrated is electron flow shown. Hence, in this book, the section on cells shows electron flow (negative to positive). In most other cases, conventional current flow (positive to negative) is shown. All the rules connecting electricity and magnetism in the section on electromagnetism are worked out using conventional current flow.

Potential Difference

A potential difference (p.d.) is said to exist between two points if a current flows when they are connected by a conductor. Thus, a cell has a potential difference between its

terminals. And a conductor carrying a current must have a potential difference between its ends. Like e.m.f., p.d. is measured in *volts* (V), and is often referred to as the *voltage* between the two points.

Ohm's Law

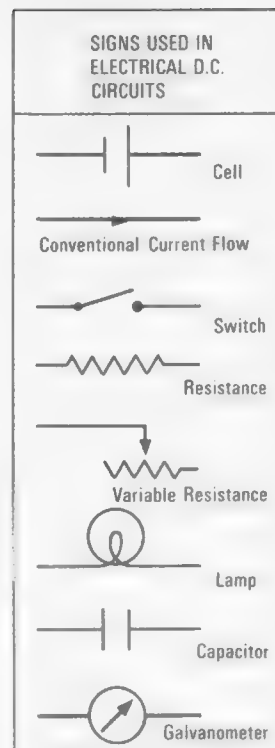
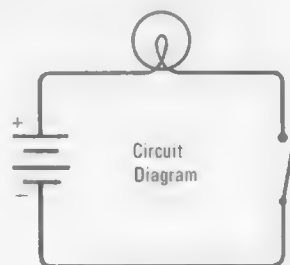
The strength of the current (I) that flows through a conductor with a potential difference (V) between its ends depends on two factors: the size of the potential difference and the extent to which the conductor opposes, or *resists*, the passage of current through it. This opposition to current flow is called the *resistance* (R) of the conductor. It is measured in units called *ohms* (Ω), after the German scientist Georg Ohm (1787–1854). By experiment, Ohm discovered that the ratio V/I is constant for some conductors under fixed physical conditions (such as temperature). This constant is the resistance of the conductor under those conditions. Hence, $V/I = R$. This relationship can be arranged to give $I = V/R$, or $V = IR$.

A *resistor* is a component which has the property of resistance. Its resistance may be fixed or variable.

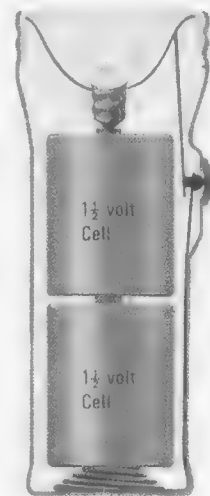
Power

Power is the rate at which energy is converted from one form to another. Converting energy at the rate of one joule per second is equal to a power of one *watt*.

When a direct current flows through a conductor, electrical energy is converted to heat and, sometimes, light. The rate at which this happens—the power (P) in watts—is equal to VI , where V is the potential difference between the ends of the conductor, and I is the current passing through it.



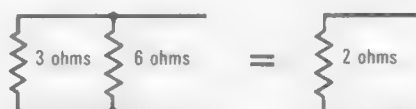
An electric torch makes up a d.c. circuit. It contains two 1.5 volt cells, a switch, and a lamp. The casing of the torch forms the rest of the circuit.



RESISTORS IN SERIES AND PARALLEL

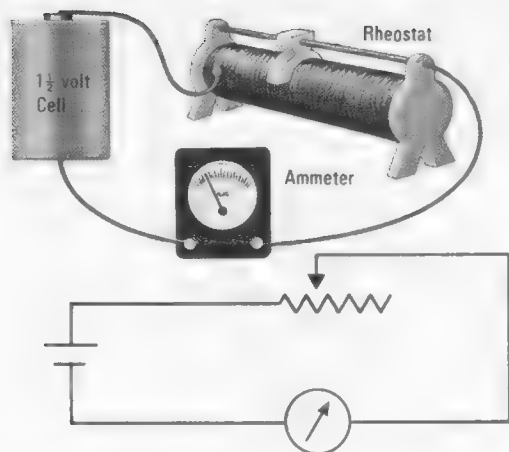


The total resistance of resistors connected in series is calculated by simply adding the individual resistances together. Therefore, if resistances of 6 ohms and 3 ohms are connected in series, the total resistance is 9 ohms.

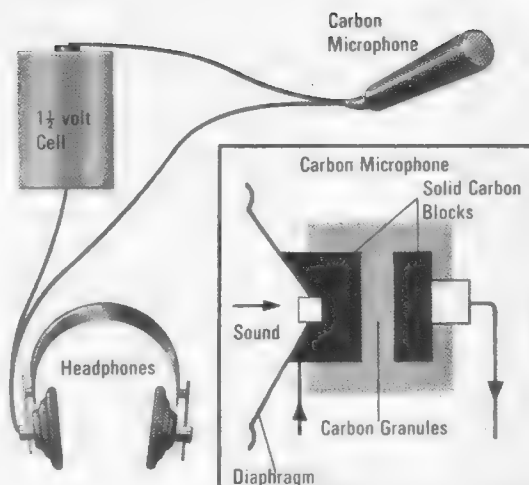


The total resistance of resistors connected in parallel is calculated by using the formula $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \dots$ etc.

In the example given $\frac{1}{R} = \frac{1}{3} + \frac{1}{6} = \frac{1}{2}$. Therefore $R = 2$ ohms.



Left: A rheostat (variable resistor) can be used to vary the current flowing in a circuit. Right: the carbon microphone is a special kind of variable resistor. Sound waves striking the microphone cause the carbon granules to be alternately compressed and expanded. The resistance of the granules is lowest when they are compressed together. The current produced by the battery therefore varies in the same way as the sound, which is reproduced by the headphones.



CAPACITANCE AND CHARGE

Electric charge (Q) is measured in units called *coulombs*. One coulomb is the quantity of electricity that flows in one second when the current is one ampere. As an ampere is a flow of 6.28×10^{18} electrons per second, one coulomb is equal to a charge of 6.28×10^{18} electrons.

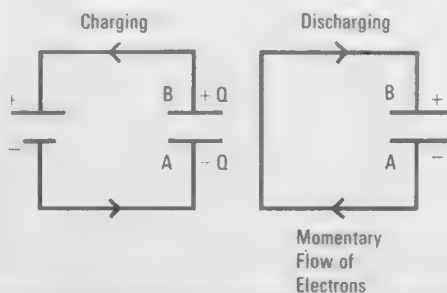
A *capacitor*, or *condenser*, is a device that can store electric charge. In its simplest form, the capacitor consists of two metal plates separated by air, or some other insulator. If the plates are connected to the terminals of a cell, a surge of electrons flows momentarily from the negative terminal into one plate, and from the other plate to the positive terminal of the cell. This displacement of electrons charges the capacitor until the potential difference (V) across its plates is equal to the p.d. across the terminals of the cell. When this state has been reached, no more electrons are displaced.

If the capacitor is now disconnected from the cell and its plates are connected by a conductor, electrons will flow from one plate to the other until the capacitor is fully discharged. Even if the capacitor is not connected to anything, its charge will slowly leak away. This is because the insulator between its plates can never be perfect, and will allow electrons to drift across gradually.

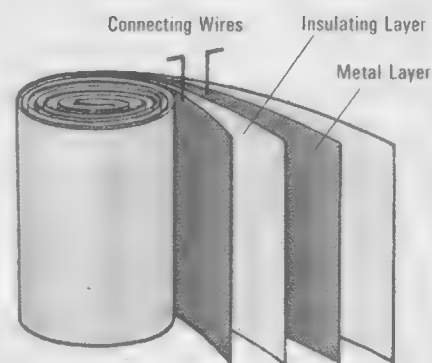
For a given capacitor, the ratio of the stored charge (Q coulombs) to the p.d. between its plates (V volts) is constant. This ratio is called the *capacitance* (C) of the capacitor and is measured in farads. Hence, $C = Q/V$.

The capacitance of a capacitor is determined by the size of its plates, the distance between them, and the nature of the *dielectric*—the insulating material between the plates.

Capacitors with fixed plates are widely used in electronic equipment to obtain a steady potential difference from a pulsating supply. Capacitors with moving plates are used in radio sets to tune in, or select, the required signal.



Above: These huge capacitors are used to store a large quantity of electrical energy. They power one of the most powerful flash X-ray generators. When operated from a 13 million volt pulse, the machine generates a radiation dose equivalent to that of 12,000 dental X-rays.



Below left: Connecting a capacitor to a cell causes a burst of electrons to flow into one of the plates (A) and out of the other (B). This quickly charges the capacitor. Once this has happened, no more electrons flow. If Q coulombs flow during charging, the plates acquire charges of $+Q$ and $-Q$, and the capacitor is said to have a charge of Q coulombs. Q can be calculated from the formula $Q = CV$, where C is the capacitance in farads, and V is the potential difference in volts across the plates. If the charged capacitor is disconnected from the cell, the p.d. across its plates will be found to be equal to the e.m.f. of the cell. The capacitor can be discharged by connecting its plates together. A momentary electron flow from one plate (A) to the other (B) will result.

A modern capacitor of the tubular type consists of two layers of metal foil and two layers of insulating material. The layers are sandwiched together and rolled up into a tube. In some tubular capacitors, the insulating layers are paper.

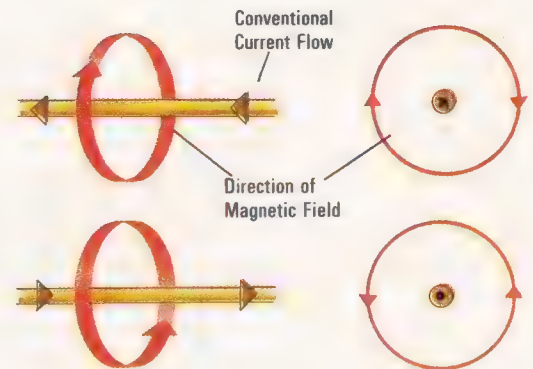
Electromagnetism

In 1819, Hans Christian Oersted, a Danish physics professor, was giving a lecture on electricity. To demonstrate the heating effect of an electric current, Oersted connected the ends of a wire to the terminals of a battery. A heavy current flowed through the wire and, as expected, it became warm. But something unexpected happened too. A nearby compass needle deflected when the wire carried a current. Only when the wire was disconnected from the battery did the needle point North again. Quite by chance, the professor had discovered *electromagnetism*—magnetism formed by an electric current. When the current flowed through the wire, it created a magnetic field, and this deflected the needle—just as if a permanent magnet had been placed near the compass.

Scientists in other countries soon started their own investigations into this new field of science. In France, Dominique Arago found that a wire loop carrying a current produced a greater magnetic effect than a straight wire. This led other experimenters, including André Ampère, to produce strong magnetic fields by passing currents through large coils of wire. Ampère noted the important fact that a coil carrying a current has north and south magnetic poles—exactly like a bar magnet. In other words, the coil acted as an electric magnet, or *electromagnet*.

In 1825, the English physicist William Sturgeon found that the strength of an electromagnet could be increased greatly by placing an iron rod inside the coil. This led directly to the production of highly efficient electromagnets like those used today. An early model made by the American scientist Joseph Henry in the late 1820s could lift over $1\frac{1}{2}$ tons.

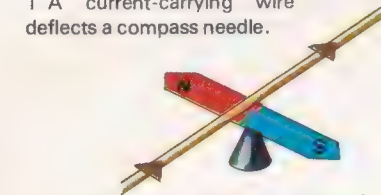
MAXWELL'S CORKSCREW LAW



When a current flows in a wire, a magnetic field is set up around the wire. The direction of this field—that is the direction in which it would make the north pole of a compass needle point—is given by the direction in which a corkscrew must turn if it is to be screwed in the direction of the current. In the top diagram, the cross indicates that the conventional current flow is away from the observer (think of the cross as the tail of an arrow). The direction of the magnetic field is therefore clockwise. In the bottom diagram the point (tip of an arrow) indicates that the current is flowing towards the observer. The direction of the magnetic field is therefore anticlockwise.

DEVELOPMENT OF THE ELECTROMAGNET

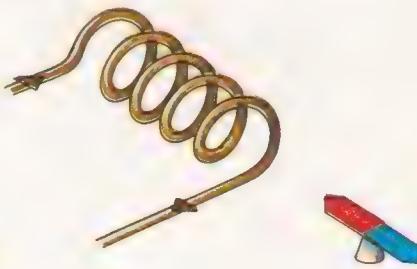
1 A current-carrying wire deflects a compass needle.



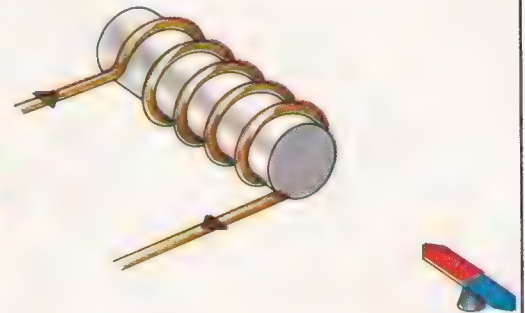
2 The magnetic effect of a current is greater in a loop of wire.



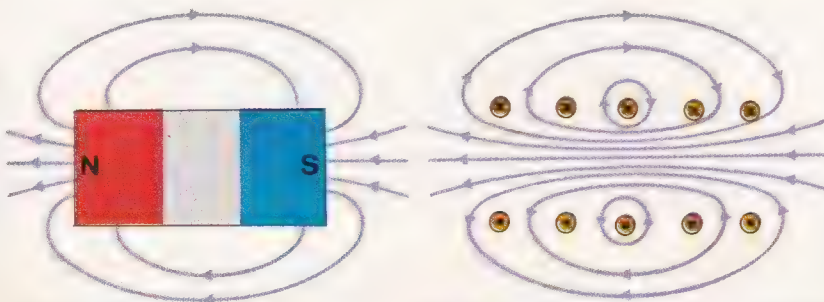
3 A coil of wire has a greater effect than a single loop of wire.



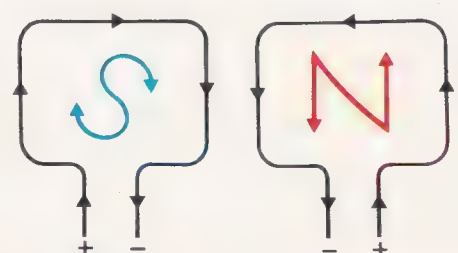
4 Winding the coil on an iron rod increases the electromagnetic effect still further.



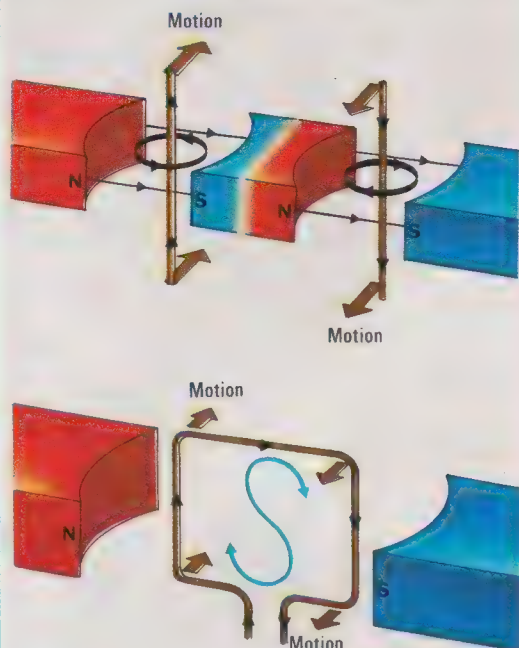
5 The direction of the magnetic field around each wire of the coil can be found by using Maxwell's corkscrew law. The individual fields combine to form the pattern shown in the diagram. This field is identical to the magnetic field produced by a bar magnet. The coil therefore has a north pole at one end and a south pole at the other when a current is passed through it.



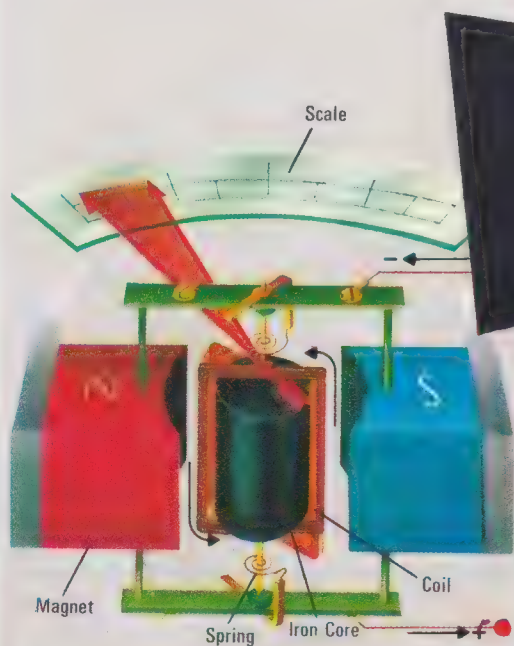
6 A quick way to find whether the end of a coil is a north (N) or south (S) pole.



THE MOTOR EFFECT



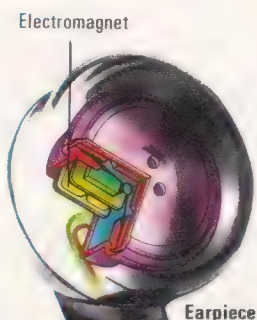
If a current is passed through a wire in a magnetic field, it will tend to move. The direction of motion depends on the directions of the field due to the magnet and the field due to the current through the wire. On one side of the wire, the like field of the magnet repels the wire. On the other side, the unlike field of the magnet attracts the wire. The motor effect will cause a pivoted loop or coil of wire carrying a current to twist in a magnetic field. Moving coil meters and some electric motors make use of this effect. The simplest method of finding which way the loop will twist is to consider its magnetic poles. Here, the south pole of the loop must twist to face the north pole on the left.



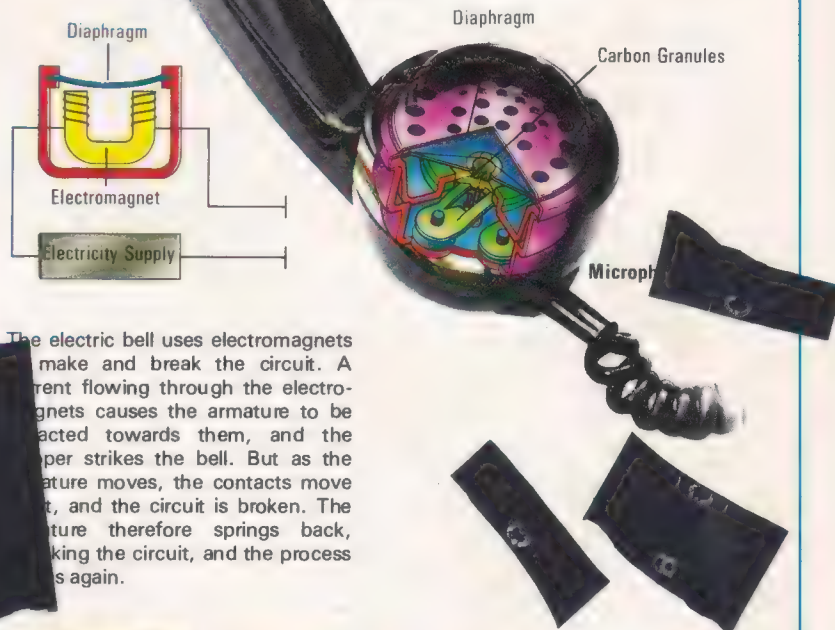
In a moving coil galvanometer (above) a current flowing through the coil makes it tend to turn against the opposing force of the springs. The deflection of the needle is proportional to the strength of the current. This galvanometer is used in the moving coil ammeter and voltmeter.

ELECTROMAGNETS IN USE

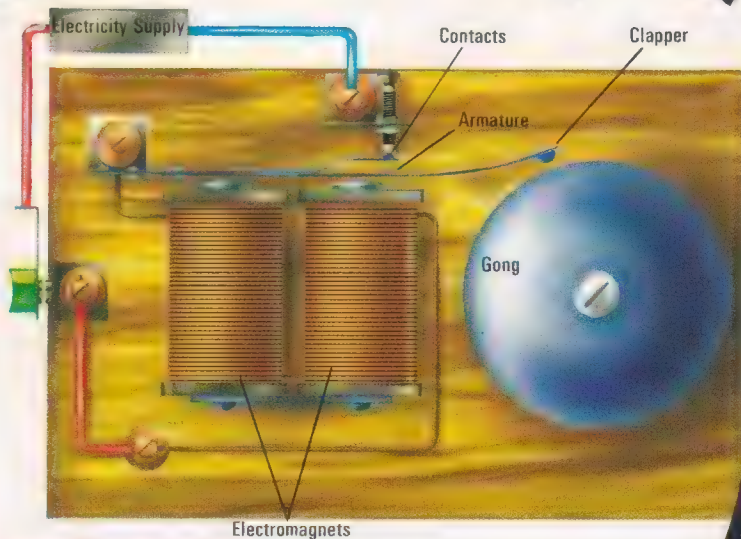
Strong electromagnets are used in industry to lift heavy steel and iron weights, such as the scrap metal shown in the photograph.



A telephone handpiece has electromagnets in the earphone. A varying direct current is caused by the voice of the speaker at the other end of the line. This current causes the electromagnets, and hence the diaphragm, to vibrate, and sound waves are produced. The microphone is a carbon microphone (see page 117).



The electric bell uses electromagnets to make and break the circuit. A current flowing through the electromagnets causes the armature to be attracted towards them, and the clapper strikes the bell. But as the armature moves, the contacts move apart, and the circuit is broken. The armature therefore springs back, making the circuit, and the process starts again.

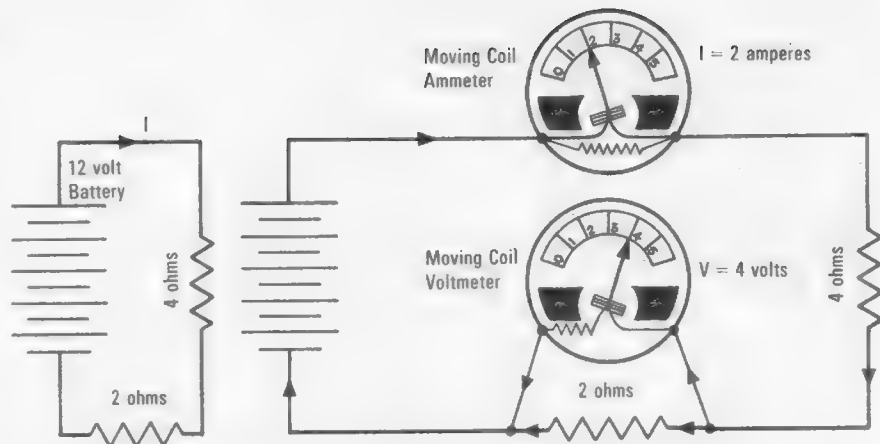


While many scientists concentrated on making stronger electromagnets, others investigated the *motion* produced by an electric current. The fact that a compass needle moved when a current flowed in a nearby wire provided a means of detecting current flow. Several scientists used this principle to make extremely sensitive current-detecting devices called *galvanometers*. These consisted of a magnetic compass mounted inside a coil of wire. Even a small current flowing through the coil would produce a magnetic field strong enough to deflect the needle noticeably.

Other instruments developed from a principle first demonstrated by Ampère in 1821. Ampère showed that a wire could be made to move by passing a current through it in the presence of a strong fixed magnet. The moving-coil ammeters and voltmeters in use today are direct applications of this principle.

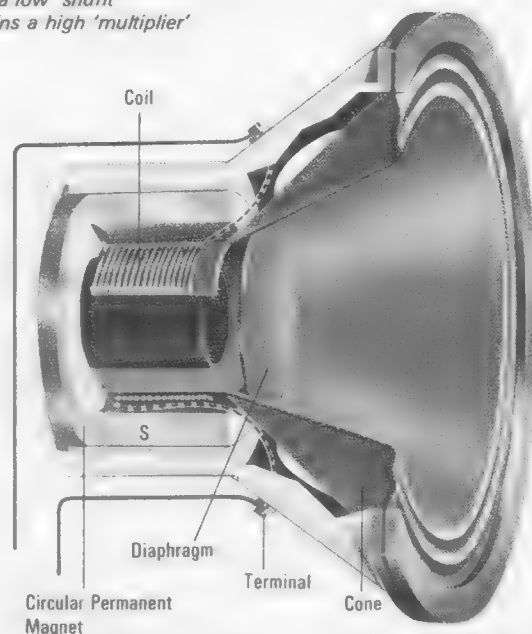
The English scientist Michael Faraday was the first to build a device that produced continuous motion when a current flowed through it. Faraday demonstrated his 'electrical rotations' in 1821. His apparatus, the first electric motor, consisted of a suspended wire that dipped in a trough of mercury containing a bar magnet. When it carried a current, the wire would rotate around the magnet. This apparatus was not powerful enough to do useful work, but it did demonstrate the important principle that a current could produce continuous motion. Later developments, mainly the use of electromagnets instead of a single current-carrying wire, resulted in the efficient electric motors in use today.

As an electric current could produce magnetism, it seemed likely to Faraday that magnetism could produce electricity. By

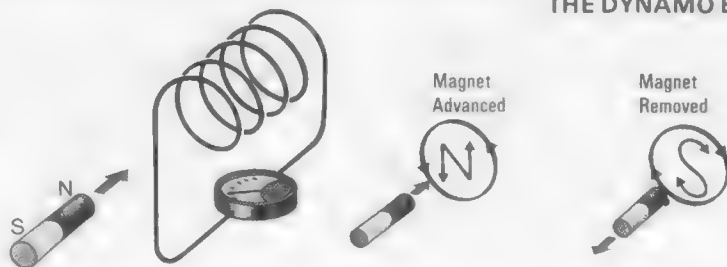


A moving coil ammeter is used to measure current, and a moving coil voltmeter is used to measure the potential difference across a resistance. The ammeter is a galvanometer that contains a low 'shunt' resistance. The voltmeter contains a high 'multiplier' resistance in series.

A moving coil loudspeaker uses the motor effect to convert electric signals into sound waves. The signals are fed to a coil, which is positioned between the poles of a circular permanent magnet. Variations in signal strength and direction cause the coil to move to and fro. This vibrates the attached cone, which emits sound waves corresponding to the varying currents in the coil.

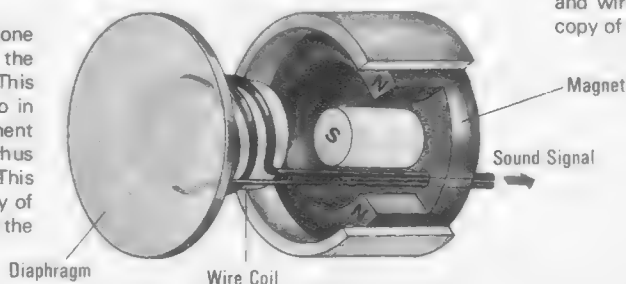


THE DYNAMO EFFECT

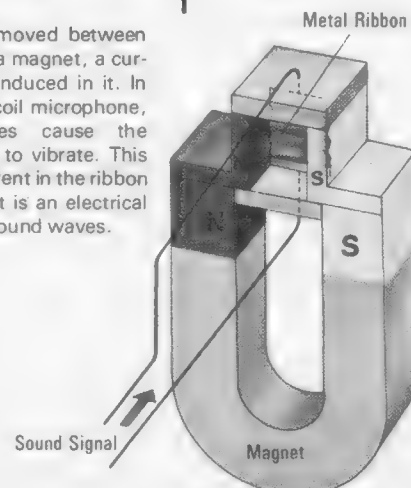


Moving a magnet towards or away from a coil causes a current to flow through the coil. By Lenz's law, the current induced in the coil opposes the motion causing it. When the north pole of a magnet is moved towards the coil, the current direction is such that it sets up a north pole to oppose the motion of the magnet. If the magnet is moved away, a south pole is set up and the current is reversed.

In a moving coil microphone sound waves make the diaphragm vibrate. This moves the coil to and fro in the field of the permanent magnet. An e.m.f. is thus induced in the coil. This e.m.f. is an electrical copy of the sound waves striking the diaphragm.

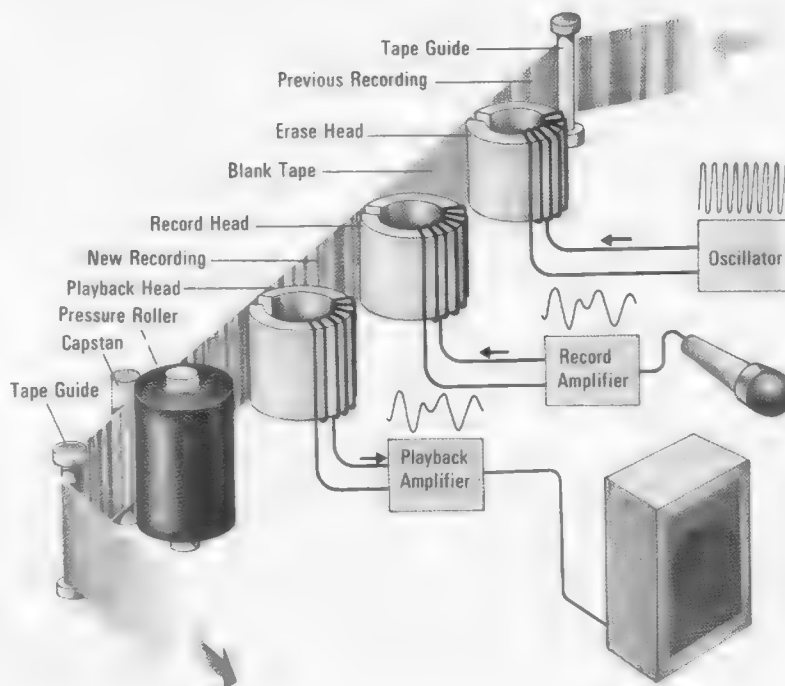


If a wire is moved between the poles of a magnet, a current will be induced in it. In the moving coil microphone, sound waves cause the metal ribbon to vibrate. This sets up a current in the ribbon and wire that is an electrical copy of the sound waves.



TAPE RECORDING

In a tape recorder, sounds are recorded as a magnetic pattern on tape. The tape is made of plastic, and has a coating of magnetic iron oxide on one side. In the recorder shown, the rubber pressure roller pushes the tape against the capstan. As the capstan rotates, it pulls the tape past three electromagnetic devices called tape heads. The tape first passes the erase head, which carries a rapidly alternating current produced by an oscillator. This current gives rise to a rapidly changing magnetic field, which destroys any existing recording on the tape. The erased tape then passes the record head, which carries a varying current, corresponding to the sound signal to be recorded. This current produces a changing magnetic field, which permanently magnetizes the tape as it passes the head. A signal is induced in the playback head when the magnetized tape passes it. This signal can be amplified and reproduced as a copy of the original sound. Professional recorders, like the one shown here, have separate record and playback heads, so that the recording can be checked while it is being made. Most domestic tape recorders have only two heads—an erase head and a dual-purpose record/playback head. Some professional machines can record 32 separate tracks on tape two inches wide.



Above: Hans Oersted (1777-1851) was the first person to show that an electric current produces a magnetic field. Below: Michael Faraday (1791-1867), went on to show that a magnetic field can be used to produce an electric current.



1831, he had discovered how this could be done. He showed that the *motion* of a permanent magnet would produce electricity in a nearby coil of wire. And he got the same result when he kept the magnet still and moved the coil instead. Faraday's apparatus, the first generator using electromagnetic principles, supplied a pulse of current each time the magnet or coil was moved. In modern generators, coils rotate in a magnetic field to produce a continuous supply of electricity.

Induction

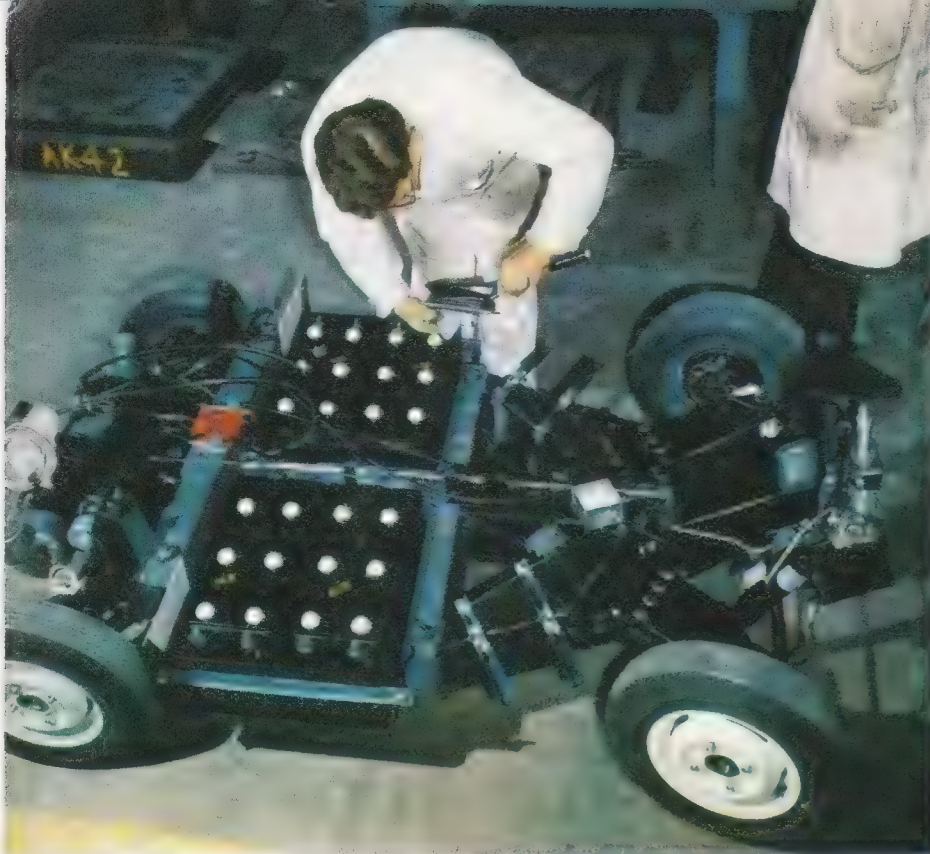
Faraday's primitive generator was the first device to demonstrate *electromagnetic induction*—the production of an electromotive force by a changing magnetic field. An e.m.f. produced in this way is said to be *induced*.

In later experiments, Faraday used an electromagnet in place of the bar magnet and obtained identical results. He then found that he could induce electricity in a coil without moving any of the apparatus. Each time he switched the electromagnet on or off, a galvanometer connected to a nearby coil deflected, indicating a momentary current. To increase the effect, Faraday wound two coils of insulated wire on an iron former. One of these coils was used as an electromagnet. The action of connecting or disconnecting a battery produced strong pulses of current through a galvanometer connected to the second coil. The changing magnetic field produced by the intermittent current in the first coil had induced an e.m.f. in the second coil.

From observations made during his experiments, Faraday formulated his law of *electromagnetic induction*. This states that the e.m.f. induced in a conductor is proportional to the rate at which the magnetic flux changes. The

direction in which the e.m.f. acts and, hence, the direction in which the induced current flows, is given by a law formulated in 1834 by Heinrich Lenz, a German physicist. *Lenz's law* states that the induced e.m.f. and current are in such a direction as to oppose the change producing them. Suppose, for example, that the north pole of a magnet is moved towards a coil of wire with its ends connected. The induced e.m.f. would make a current flow in such a direction that the end of the coil nearest the magnet would become a north pole. As like poles repel each other, the coil would oppose the magnet's movement towards it. Moving the north pole of the magnet away from the coil would produce a south pole at the near end of the coil. As unlike poles attract, the coil would oppose the magnet's movement away from it. The mechanical energy used up in overcoming this opposition is equal to the electrical energy generated in the coil. This is in accordance with the law of conservation of energy.

When Faraday wound two coils on the same iron core, he had made the first *transformer*. But Faraday did not realize that it could be used to transform e.m.f.s from one voltage to another. He was concerned only with the transference of energy from one coil to another. Joseph Henry had noted the same effect at about the same time as Faraday, and went on to make another important discovery. He found that a changing current in a coil induces an e.m.f. in that same coil. This effect is called *self-induction*. The property that causes it is called *inductance* and is measured in units called *henrys*. A coil has an inductance of one henry if an e.m.f. of one volt is induced in it, when the current passing through it changes at the rate of one ampere per second.



An electric car uses a motor powered by several batteries. Cars powered by electricity have several advantages over those powered by internal combustion engines. They are quiet, relatively cheap to run, and they do not pollute the atmosphere. The main disadvantage is that an electric car has a limited range. It cannot travel far before its batteries have to be recharged — a process that takes several hours.

motor has become almost a necessity, both in industry and in the home.

Although electric motors have changed a lot since Faraday's 'electrical rotations' of 1821 (see page 119), the fundamental principle of operation remains the same: passing a current through a conductor tends to make it move in a magnetic field.

D.C. Electric Motors

In a simple d.c. motor, a pivoted coil of wire, wound on an iron core, is mounted in the field of a fixed permanent magnet. Connections from a battery to the coil are made via two fixed carbon blocks called *brushes*. These rub against a split metal cylinder called a *commutator*, each half of which is connected to one end of the coil. As in the moving-coil ammeter, the coil acts as an electromagnet. Passing a current through the coil magnetizes it, and it starts to turn to align its north and south poles with the south and north poles of the permanent magnet. Here, the similarity with the ammeter ends, for the motor has no springs to restrict the coil's movement. So the coil turns freely to face the poles of the magnet. But, like any moving body, the coil cannot stop immediately, and its inertia carries it past the poles of the magnet. As the coil passes the alignment position, the *commutator* reverses its connections with the brushes, thus reversing the direction of the current through the coil. This reverses the magnetic poles of the coil,

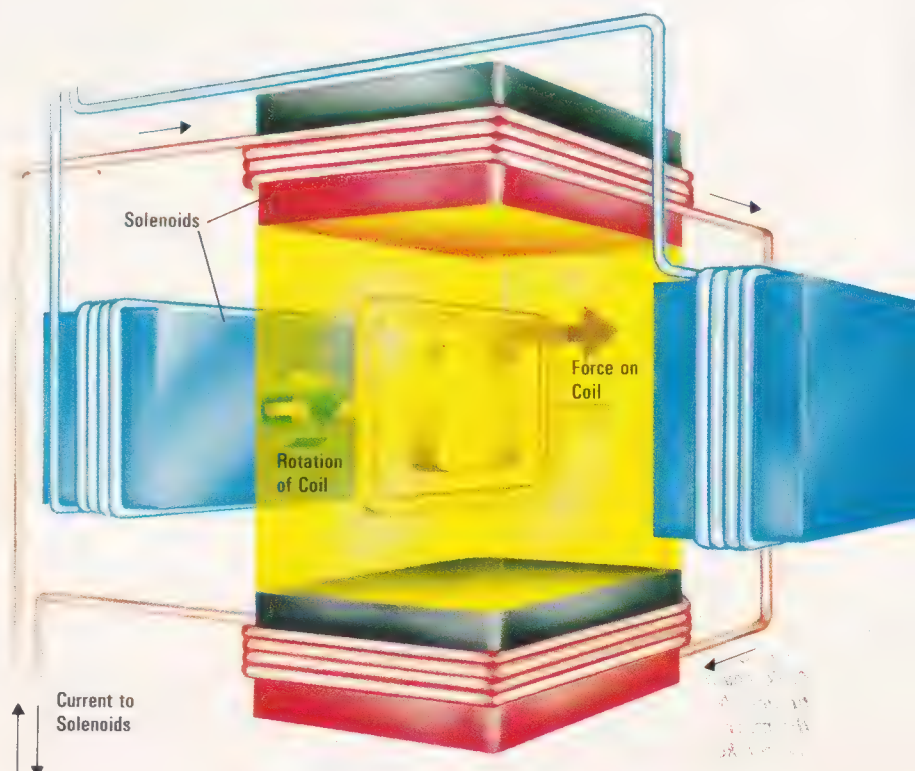
Motors and Generators

Electric Motors

The Tsar of Russia was delighted with his electric paddleboat. Its battery-powered motor, built by Hermann de Jacobi in 1834, hummed quietly as it propelled the small craft along the River Neva. At about the same time, an American engineer called Thomas Davenport used an electric motor to drive a small locomotive around a circular track. Electric transport had arrived. And in factories, electric motors were being installed to operate a variety of machines.

These early electric motors were highly inefficient, and the larger models required enormous batteries of acid-filled cells. But, by the 1850s, improvements in motor design had transformed the interesting novelty into a commercial success. Since then, the electric

An induction motor is so called because the driving force is due to an electric current induced in a rotor, due to its interaction with a magnetic field. The motor in the diagram consists of four solenoids (coils wound on iron bars) and a closed loop of wire. When alternating currents are passed through the solenoids, they create a rotating magnetic field. This field cuts the closed loop, and thus induces an electric current in it. The loop therefore starts to turn. As it turns faster it tries to catch up the rotating magnetic field, and the difference between the two speeds gets smaller. The size of the induced current, and hence the size of the driving force, also get smaller. The loop of wire therefore settles down to a steady speed, which is lower than that of the rotating magnetic field.



causing each one to be repelled from the fixed pole it has just passed and attracted to the other side of the magnet. As a result, the coil continues to turn in the same direction. The commutator reverses the current in this way every half-turn, so the coil rotates continuously.

Simple d.c. motors like this have limited use. One problem is that the torque, or turning force, produced varies considerably, being highest when the plane of the coil coincides with the direction of the field of the permanent magnet. To overcome this defect, the rotating part, called the *rotor*, or *armature*, can be wound with several coils. These are positioned evenly around the rotor and connected to a commutator with one pair of segments for each coil. This arrangement produces a high torque with little variation in strength.

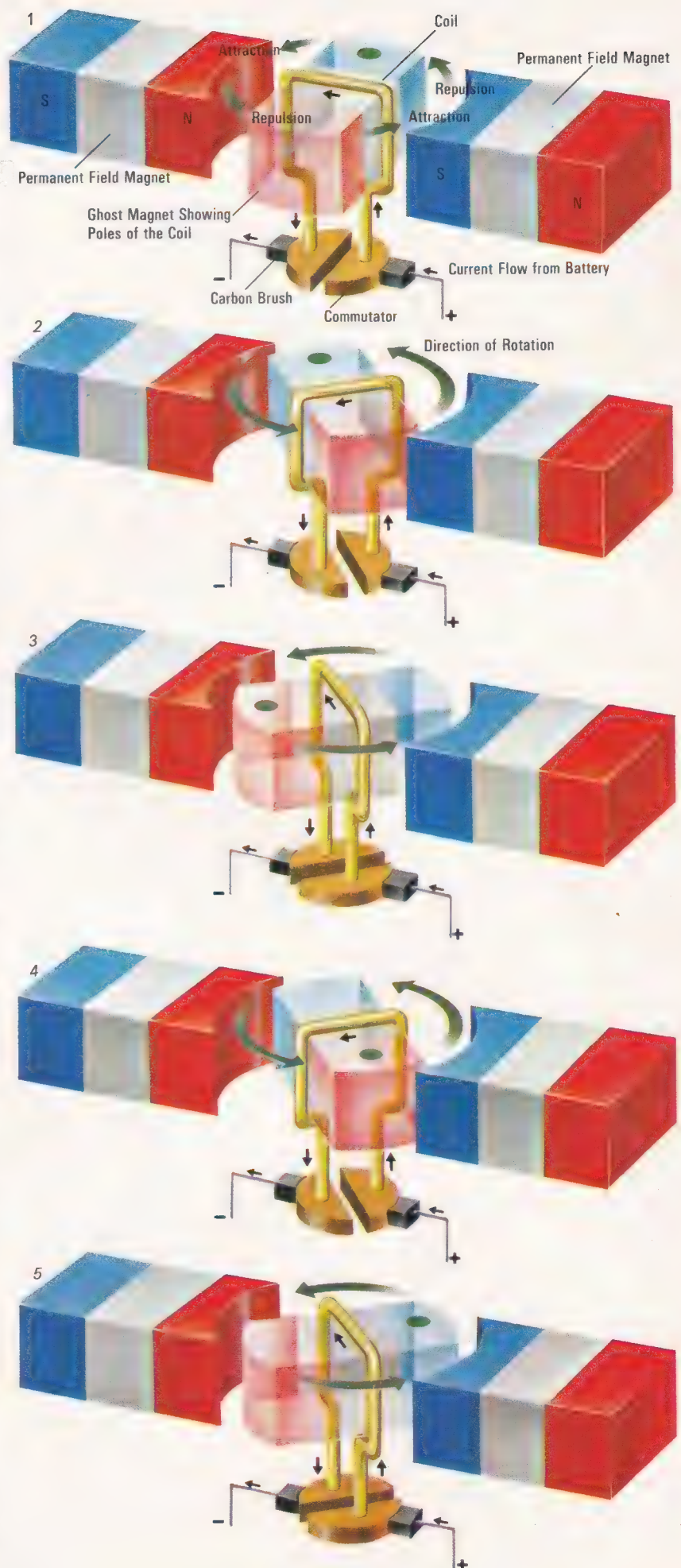
The torque produced by an electric motor depends also on the strength of the field in which the rotor turns. By using a powerful electromagnet instead of a permanent magnet, the strength of the field and, hence, the torque developed by the motor can be greatly increased. Electromagnets used to produce a magnetic field are called the *field coils* or *windings*. As, in this case, they make up the stationary part of the motor, they are also referred to as the *stator*. In the *series motor*, the field and armature windings are connected in series with each other. In the *shunt motor*, the two windings are connected in parallel.

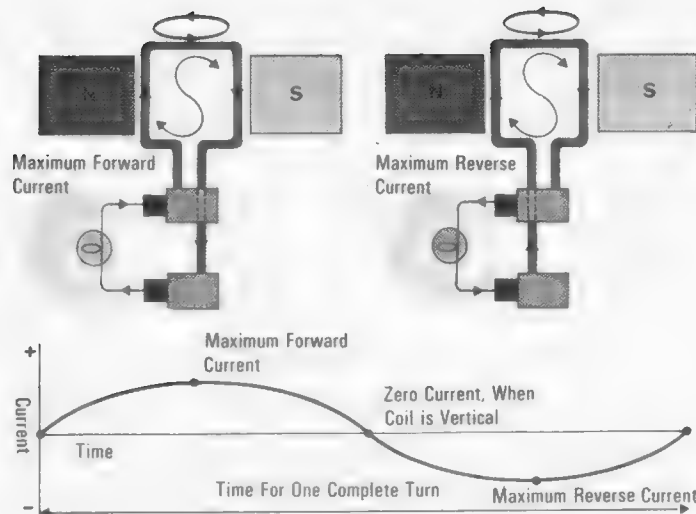
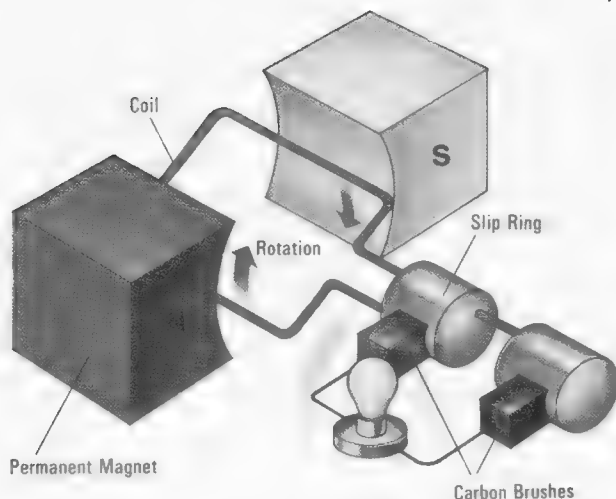
A.C. Electric Motors

Motors designed for operation from an alternating current supply take many forms. But the most common type, by far, is the *induction motor*. Alternating current passed through fixed field coils sets up a rotating magnetic field. This moving field induces currents in closed loops of wire mounted on the rotor. These currents set up magnetic fields around the wires and cause them to follow the main magnetic field as it rotates. The operation of the induction motor depends on the rotating field passing through the loops on the rotor.

The diagrams show the sequence of events during one rotation of a simple d.c. motor. For clarity, the coil has been shown as a single loop of wire. When a current flows through the coil, a magnetic field is set up, and the coil has a north and a south pole, represented here as a ghost magnet. The poles of the coil change places as the coil rotates, and so one end of the ghost magnet has been marked with a dot for easy identification. Separate permanent magnets provide a magnetic field in which the coil turns.

1. The magnetic fields interact, and forces of attraction and repulsion cause the coil to turn. 2. The poles of the coil are almost in line with the poles of the permanent magnets. And the carbon brushes are almost at the ends of the commutator segments. 3. The coil cannot stop when its poles are aligned with those of the permanent magnet. The momentum of the coil carries it past this point. At the same time, the commutator reverses the current flowing through the coil, thus reversing the magnetic poles of the coil. 4. Forces of attraction and repulsion keep the coil turning. 5. The poles of the core again pass those of the magnet, the current through the coil reverses, and the coil keeps turning.





Therefore the rotor must always turn more slowly than the rotating field. As no current has to be supplied to the rotor, the induction motor is simple to construct and reliable in operation.

In the *synchronous* motor, rotor coils energized from the electricity supply turn exactly in step, or in synchronism, with a rotating magnetic field. Synchronous motors are used in electric clocks and other devices where the running speed is critical.

Electricity Generators

Early electromagnetic generators were unimpressive. Because of their inefficiency, they generated little power and were unworthy rivals to the battery. However, by the 1860s, generators powerful enough to light arc lamps had been developed. At last, people could see the generator in action. From that time, the interest in generators grew rapidly. And, as more and more electrical appliances were

manufactured, the demand for electricity increased too. By 1900, great advances in generator design had been made. And many countries had cable systems to distribute electricity produced by huge generators. Most of these were turned by steam engines. Today, the largest generators produce over one thousand million watts of electricity.

How Generators Work

A simple generator resembles a simple electric motor. A coil, wound on an iron core and mounted so that it can rotate, is positioned between the poles of a permanent magnet. Rotating the coil makes it cut the magnetic field of the permanent magnet, so an e.m.f. is induced in the coil. The field can be thought of as imaginary magnetic field lines joining the poles of the magnet. As the coil rotates, the angle at which it cuts through these lines changes all the time. Therefore, the rate at which it cuts field lines changes too. This

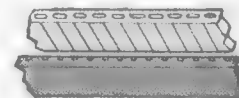
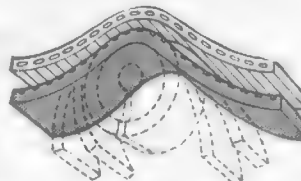
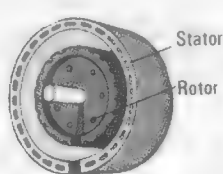
Above: In a simple a.c. generator an alternating current is produced as the coil rotates in the magnetic field. By Lenz's law, the generated current sets up a magnetic field that tends to oppose the motion. Therefore, the face of the coil that is approaching the south pole of the magnet must also be a south pole. This decides the direction of the current flow. When the coil is horizontal, the maximum current is being generated, because the coil is cutting vertically across the magnetic field. As the coil reaches the vertical position, the current falls to a minimum. As it passes the vertical position the direction of current flow reverses.

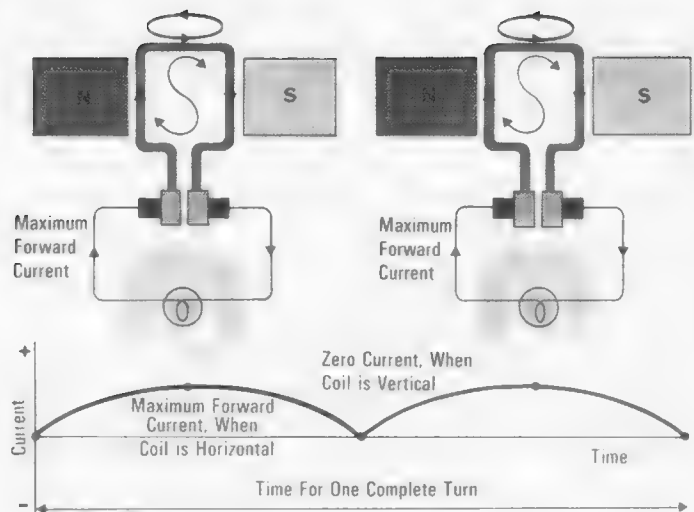
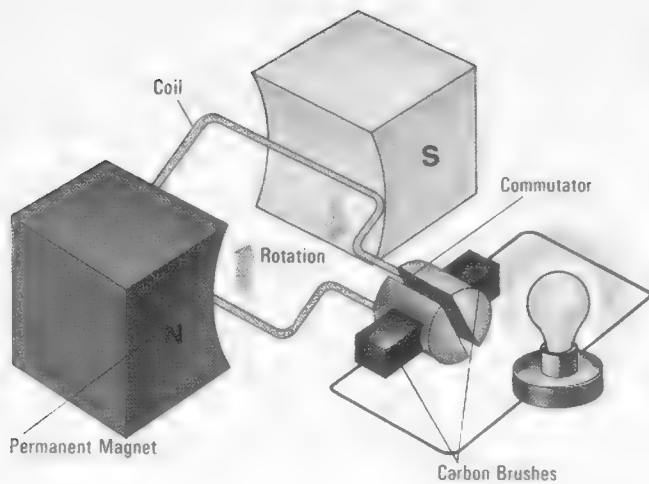
LINEAR INDUCTION MOTOR

A conventional motor produces rotary (turning) motion. It has a fixed outer *stator* and an inner *rotor*, which turns. A linear motor is designed to produce motion in a straight line. It may be thought of as an 'unwrapped conventional motor'. If such a motor is cut open and flattened out and the 'rotor' is then fixed, the 'stator' will be induced to move horizontally by the magnetic field.

This principle has been used in a number of designs, even as far back as the late 1800s. But the first linear motor to be built was a tubular d.c. motor that was used to launch missiles in 1917. Many people are now convinced that the linear electric motor could be used in railway systems. The photograph shows a prototype for a tracked hovercraft that uses a linear motor.

Linear motors have the advantage of having no parts that move against each other. Thus there is no need for lubrication and wear and tear is reduced.





causes a corresponding variation in the strength of the induced e.m.f. The rotation of the coil also causes the induced e.m.f. to alternate, or change direction. This is because the coil windings alternately reverse the direction of their motion through the magnetic field. The result is an e.m.f. that increases from zero to a maximum, decreases to zero, increases to a maximum in the opposite direction, and then decreases again to zero.

In one type of generator, the ends of the coil are connected to metal cylinders called *slip rings*, which are mounted on the rotor. A pair of fixed carbon brushes makes contact with these rings as the rotor turns. Therefore, the e.m.f. induced in the coil appears across the brushes. This alternating e.m.f. gives rise to an alternating current in a conductor connecting the brushes. For this reason, the generator described is called an *a.c. generator*, or *alternator*.

In a simple *d.c. generator*, the coil is connected to a commutator instead of slip rings. The current flowing through the coil still alternates. But the commutator reverses the connections to the carbon brushes every half-turn, so the current always leaves the coil through one particular brush and returns through the other one. Although the current supplied by such a generator always flows in the same direction through a conductor connecting the brushes, its strength varies as the rotor turns. This effect can be reduced considerably by arranging several coils around the rotor, each one being connected to a separate pair of segments on the commutator.

Today, only the smallest generators contain permanent magnets. In most generators, electromagnets are used because they can provide a much stronger magnetic field. In a.c. generators, these *field coils* are usually energized by a separate d.c. generator. Most d.c. generators, however, make use of an effect called *self-excitation* and need no separate supply for the field coils. A small amount of magnetism, known as *residual magnetism*, is always present in the iron cores of the field coils. This causes a small current to be generated when the rotor turns. Part of this

generated current is passed through the field coils, increasing the strength of the field and, hence, increasing the generated current. In this way, the generated current builds up rapidly to full output.

In any generator, the part in which the generated current is induced is called the *armature*. In the generators discussed so far, the armature has always been the *rotor*, or rotating part of the machine. In d.c. generators, this is useful, as a commutator can be fitted to the rotor to carry out the switching necessary to produce direct current. But in a.c. generators no commutator is required, so the armature can be stationary and the field coils made to rotate. This arrangement is particularly useful in powerful generators. For it means that the slip rings and carbon brushes carry the relatively small current supply for the field coils instead of the extremely large generated current. This reduces power losses, thus increasing the generator's efficiency.

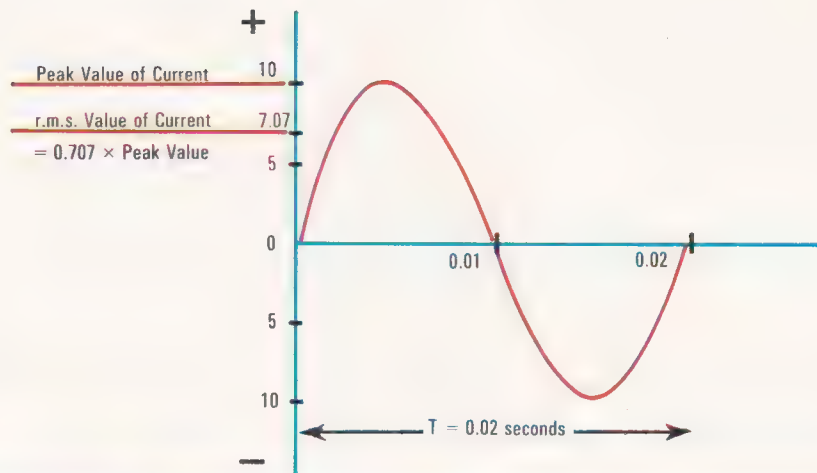
Above: In a simple d.c. generator the current is generated in exactly the same way as in the a.c. generator. The current direction in the coil reverses each time the coil passes the vertical position. But in a d.c. generator, the connections of the split ring commutator also reverse, and the current direction in the circuit remains the same.

Below: Some power stations are situated where they can harness natural forms of energy. In this power station, the generators are turned by the water piped from the melting snow in the mountains above.



Alternating Current

Alternating current (a.c.) changes all the time. It builds up to a maximum flow in one direction, decreases to zero, builds up to a maximum in the opposite direction, and then returns to zero once more. This complete sequence, or *cycle*, repeats, the rate at which it repeats being called the *frequency* of the alternating current. The mains current supplied to most houses in Europe has a frequency of 50 cycles per second. This is usually expressed as 50 hertz (50 Hz), the hertz being a unit equal to one cycle per second. The time taken for an alternating current to go through one complete cycle is called the *periodic time*, or *period*.

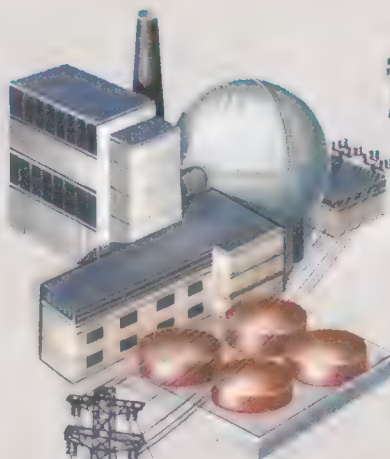


ELECTRICITY SUPPLY AND DEMAND

Electricity is our most convenient form of energy. It is easy to generate, distribute, and use. Huge generators in power stations provide our mains electricity supply. In many power stations, a fuel, such as coal, oil, or gas, is burnt to provide heat for boiling water. The steam produced turns turbines coupled to the generators. In nuclear power stations, heat from a reaction called nuclear fission turns the water to steam.

Some countries get most of their electricity from *hydro-electric* power stations. The generators are turned by moving water from a river, reservoir, or waterfall.

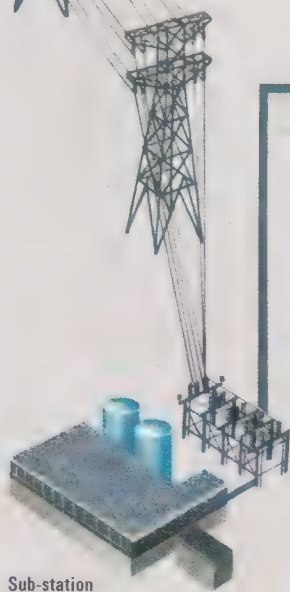
The electricity generated at a power station could be distributed at low voltage and high current, or at high voltage and low current. But the power loss in the cables is proportional to the current squared. So, in order to keep the power loss as low as possible, a small current and correspondingly high voltage are used. Huge transformers convert the output of the generators to the high voltage required for distribution. This sometimes as high as 400,000 volts. A network of cables, supported by pylons, convey the electricity to users over a wide area. Transformers reduce the voltage to a value suitable for use in shops, factories, and homes. In Britain, the mains supply to most homes is 240 volts, alternating at a frequency of 50 hertz.



Power Station



Electricity cables are supported on pylons.

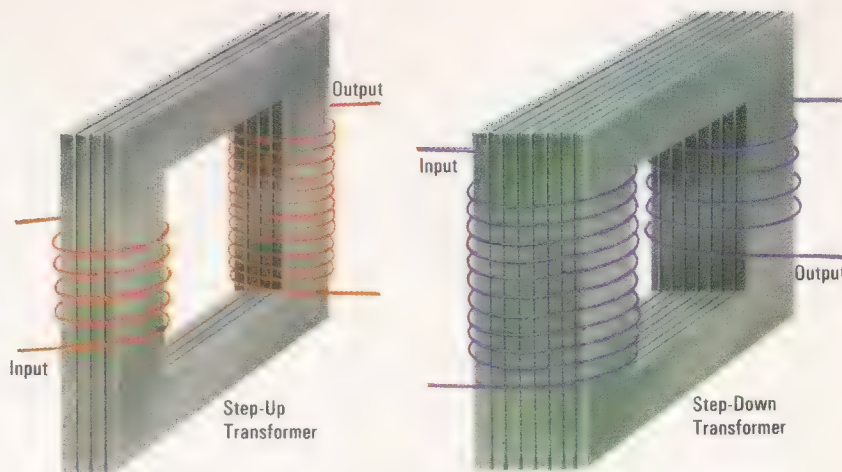


Sub-station



A current that continually changes its direction of flow might, at first, seem rather inconvenient. In fact, the opposite is true. Alternating current can be generated with greater efficiency than direct current. It can be easily transformed from one voltage to another, whereas direct current cannot. And alternating current can be easily converted to direct current, whereas the reverse process is much more complicated and less efficient.

Because an alternating current varies continuously, the problem arises as to how to describe its strength. One way is to state the maximum value it reaches. Another way is to state the *average value*. To have any useful



Opposite: The graph shows how an alternating current varies with time. As the periodic time (T) — the time taken to complete one cycle — is $1/50$ second, then 50 cycles must occur each second. The frequency of the alternating current is therefore 50 cycles per second, or 50 hertz.

Above: A transformer is used to step-up or step-down an a.c. voltage. The alternating current in the input coil induces a changing magnetic field in the iron core. This induces an alternating current in the output coil.

The final voltage depends on the number of turns in the output coil. Hence, a step-up transformer has more turns in the output coil than the input coil, and a step-down transformer has fewer turns in the output coil.

Left: Large transformers are used to convert the output of the generators in a power station to a high voltage and a low current. This is to reduce power loss in the distribution cables.

Below: One major industrial use of electricity is in the refining of aluminium by electrolysis.



Industry

Domestic Supply

Streets



A local substation distributes the electricity used in factories (top right), offices (left), streets (above), and homes (right).



In the home, the electricity supply from the substation is fed into a meter, which records how much electricity the consumer uses. From the meter board, live wires are connected through a fuse box. A fuse contains a small length of low melting point wire. If the current passing through the fuse wire becomes too great, the wire heats up (due to the heating effect of its resistance) and melts, thus breaking the circuit. Household lighting and electric appliances are operated from sockets situated around the house. Plugs must be wired up very carefully. The colour coded wires (brown — live; blue — neutral; yellow and green — earth) must be correctly connected. The earth wire is a safety device. If the live wire of an unearthed appliance should accidentally touch the metal casing, anyone touching the appliance would get an electric shock. But if the appliance is earthed, the current flows down the earth wire to the ground and the fuse is blown.

meaning, the average value would have to be taken over one complete half-cycle, starting and ending at zero strength. Over a complete cycle, the average values would be zero. Because the current flows first in one direction, then in the other direction, over a complete cycle there is no overall flow of current in any direction.

Another way of describing the strength of an alternating current is to state the strength of the direct current that produces the same heating effect when it flows through a resistor. This value is usually expressed as the *root mean square (r.m.s.)* value (see box).

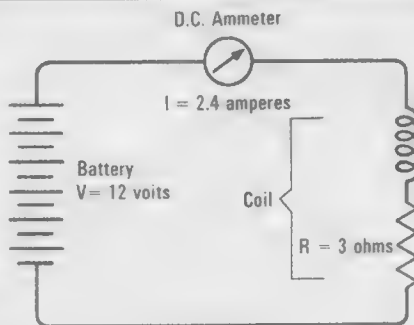
ROOT MEAN SQUARE VALUE

In a d.c. circuit, the power—the rate at which heat is produced—is given by the formula I^2R , where I is the current in amperes and R is the resistance in ohms. For an alternating current, the average, or *mean*, value of I^2 must be used to calculate the power. Taking the square root of this mean value of I^2 gives the effective value of the current, as far as heat production is concerned. This value (the square root of the mean of the current squared) is the *root mean square (r.m.s.)* value. In practice, the r.m.s. value of an alternating current or voltage is 0.707 times the peak, or maximum value. This means that the peak value is equal to $1/0.707 = 1.414$ times the r.m.s. value. When the r.m.s. value of an alternating current or voltage is known, power calculations can be made as if the current was direct. Because r.m.s. values are so convenient, they are commonly used in circuits carrying alternating current—for example, house mains supplies. Hence, if the voltage of a mains supply is said to be 240 volts a.c., this is its r.m.s. value. Its peak value, therefore, is 1.414×240 volts, which is equal to approximately 340 volts.

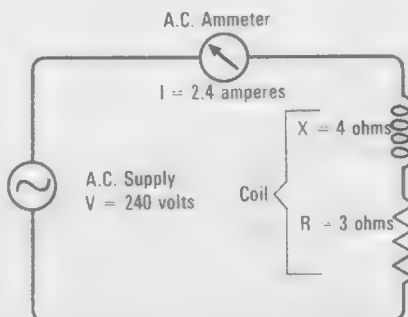
A.C. CIRCUITS

In a circuit carrying direct current the strength of the current (I) can be calculated if the e.m.f. (V) of the source and the resistance (R) of the circuit are known. The calculation for a circuit carrying alternating current is similar, except that we must substitute *impedance* (Z) for resistance. The impedance of a circuit is its opposition to the flow of alternating current through it. Like resistance, impedance is measured in ohms. The current through a d.c. circuit is given by $I = V/R$. The corresponding equation for an a.c. circuit is $I = V/Z$.

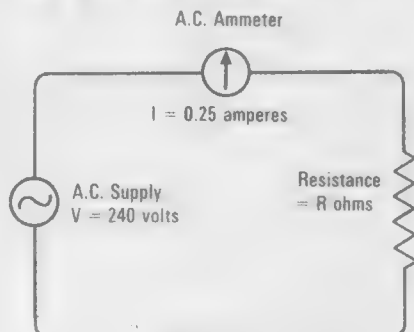
The impedance of a resistor is exactly the same as its resistance. In other words, a resistor opposes the flow of alternating current in exactly the same way as it opposes the flow of direct current. But other components behave differently. Consider, for example, a coil of copper wire having a resistance of 3 ohms. If the ends of the coil are connected to the terminals of a 12 volt battery, then the current that flows is 4 amperes. But, if the coil is connected instead to a source of 12 volts a.c., the current is lower than 4 amperes. The continuously changing current through the coil sets up a changing magnetic field. By the process of *self-induction* (see page 121), this field gives rise to an e.m.f. in the coil. And, according to Lenz's law, the induced e.m.f. opposes the current causing it (see page 121). This opposition to the alternating current is called *reactance* (X) and is measured in ohms. The impedance of a coil—that is, its overall opposition to the flow of alternating current through it—therefore consists of resistance and reactance. The impedance can be calculated from the formula $Z = \sqrt{R^2 + X^2}$. For



Above: A coil in a d.c. circuit. Only the resistance of the coil opposes the steady current (I) flowing through it. Therefore $I = V/R = 12/3 = 4$ amperes.



Above: A coil in an a.c. circuit. Both the reactance (X) and the resistance (R) oppose, or impede, the flow of the alternating current. The impedance (Z) is given by: $Z = \sqrt{R^2 + X^2} = \sqrt{25} = 5$ ohms. Therefore the current can be calculated: $I = V/Z = 240/5 = 48$ amperes.



In an a.c. circuit containing a resistance the power (P watts) is given by the formula $P = V \times I$. Hence in the circuit above, $P = 240 \times 0.25 = 60$ watts. The value of the resistance (R) can be calculated as in a d.c. circuit, $R = V/I = 240/0.25 = 960$ ohms.

example, if the resistance is 3 ohms and the reactance is 4 ohms, then the impedance is $\sqrt{9 + 16} \text{ ohms} = \sqrt{25} \text{ ohms} = 5$ ohms.

Another component that behaves differently in an a.c. circuit is the capacitor. This may seem strange, for a capacitor consists of metal plates separated by insulating material. Ignoring any imperfections in the insulation, because there is no conducting path between them. But, when a capacitor is being charged or discharged, current flows into one plate and out of the other one (see page 117). An alternating e.m.f. applied to a capacitor alternately charges and discharges it, causing current to flow to and fro in the circuit, almost as if current was actually passing through the capacitor. The current strength is given by

$I = V/Z$, where Z is the impedance of the capacitor. Impedance is given by $Z = \sqrt{R^2 + X^2}$, where X is the reactance of the capacitor. But the minute resistance of the metal plates and wires can normally be ignored. Therefore, $Z = \sqrt{X^2} = X$. So the impedance of the capacitor is equal to its reactance and the current is given by $I = V/X$.

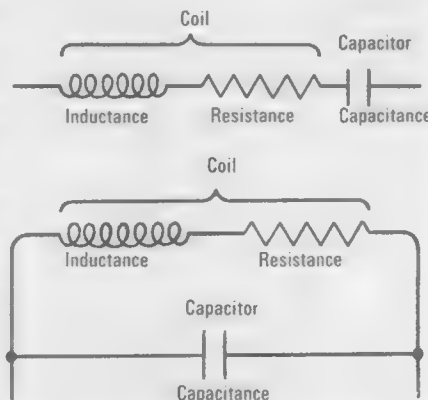
When a capacitor is being charged or discharged, the higher its capacitance, the larger is the current that flows in the circuit. So the reactance, or effective opposition to the alternating current is low when the capacitance is high, and high when the capacitance is low.

Tuned Circuits

In radio receivers, a mixture of signals picked up by an aerial passes through a tuned circuit. This is used to select, or tune in, signals of one particular frequency. Each signal passing through the circuit produces voltages across the coil and capacitor.

As the impedance of these components varies with frequency, the voltages across them will depend on frequency too. Around one particular frequency called the *resonant frequency* of the circuit, the voltages are relatively large. This is the frequency selected by the circuit. The voltages produced by signals of other frequencies are usually so small that they do not interfere with the selected signal. Normally, the capacitor is variable. Altering its value changes the resonant frequency and, therefore, the station selected. Although all coils have some resistance, this is not normally shown on circuit diagrams.

A tuned circuit contains a coil and a capacitor, either in series (top) or in parallel (bottom).



The Electronic Revolution

No other branch of science affects our lives more than electronics. In hospitals, doctors use X-ray equipment to photograph patients' bones and internal organs. Machines called electrocardiographs and electroencephalographs show the condition of the heart and brain by detecting and recording the tiny electrical signals that these organs generate. And electronic equipment permanently connected to critically ill patients automatically warns doctors if the heartbeat or breathing become dangerously irregular. Electronic pacemakers also enable many people with heart disorders to lead fairly normal lives.

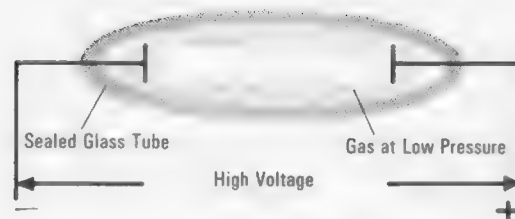
On the roads, electronic traffic-light systems control traffic flow. Police use closed-circuit television to check motorways for traffic jams. And they use radar equipment to detect when vehicles are exceeding a speed limit.

In some industries, the development of electronic equipment has led to almost complete *automation*—the automatic control of manufacturing and other processes.

Electronic devices enable the principle of *feedback* to be applied to any process. The principle of feedback is that changes in the output of a system are used to control the system itself. A change of any kind in the output of a machine or process can be converted into a corresponding electrical change. The electrical change can be amplified (strengthened) and used as a control. Suppose, for example, that a dye is being used to give a liquid a particular tint. Feedback could be used to ensure a consistent colour. In one suitable control system, a light beam passes through the tinted liquid produced onto a photoelectric cell. The e.m.f. generated by the cell is amplified and used to power an electromagnet. This pulls open a valve in a pipe supplying dye. If, for some reason, the tint starts to become too weak, the light falling on the cell increases, causing an increased e.m.f. As a result, the amplifier supplies more power to the electromagnet, so that the valve is opened farther, and the flow of dye is increased. In this way, the feedback system automatically counteracts any variations in the tint of the liquid. Electronic techniques of this kind enable relatively few people to control extremely complex processes involving hundreds of separate stages.

Another feature of modern automation is the use of computers to control machines. Feedback signals from the machines to the computer enable it to control each stage of the process. The computer can also switch over to standby equipment when a breakdown occurs, and sound an alarm to summon engineers to deal with the fault. A major advantage of a computerized system is that the whole process can be changed quickly, simply by inserting a different program (set of instructions) in the computer.

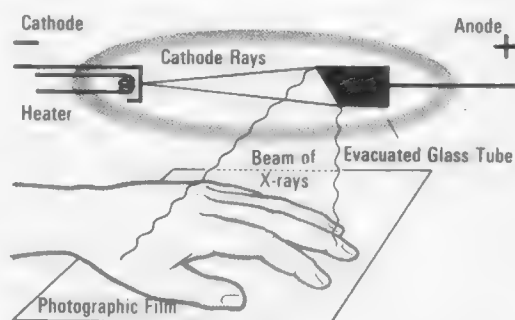
Communications is another important field that has been completely changed by electronics. Automatic telephone exchanges and satellite links enable people to dial direct to friends living on the other side of the world. And radio and television enable us to see and hear astronauts as they journey through space.



Above: In a discharge tube containing gas at low pressure, the gas glows when a high voltage is applied across the two electrodes. This effect is used in neon and sodium lighting.

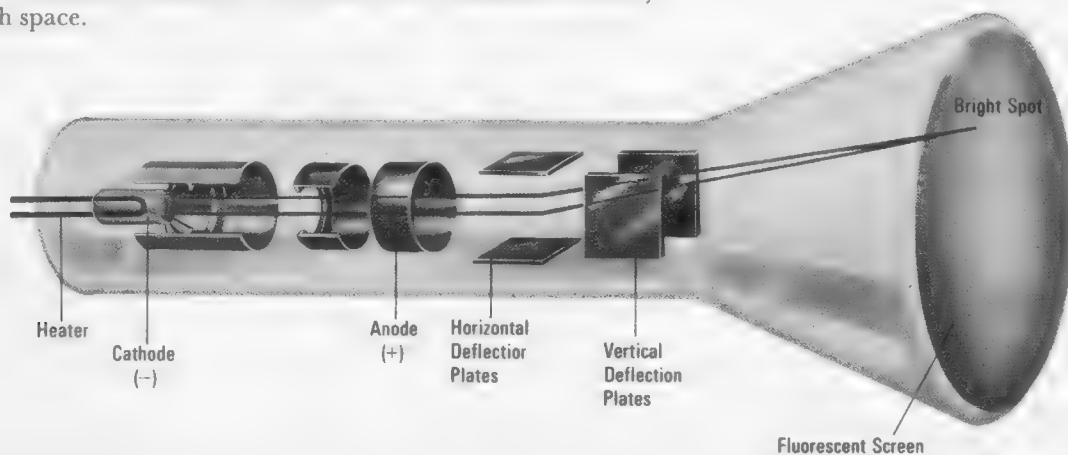


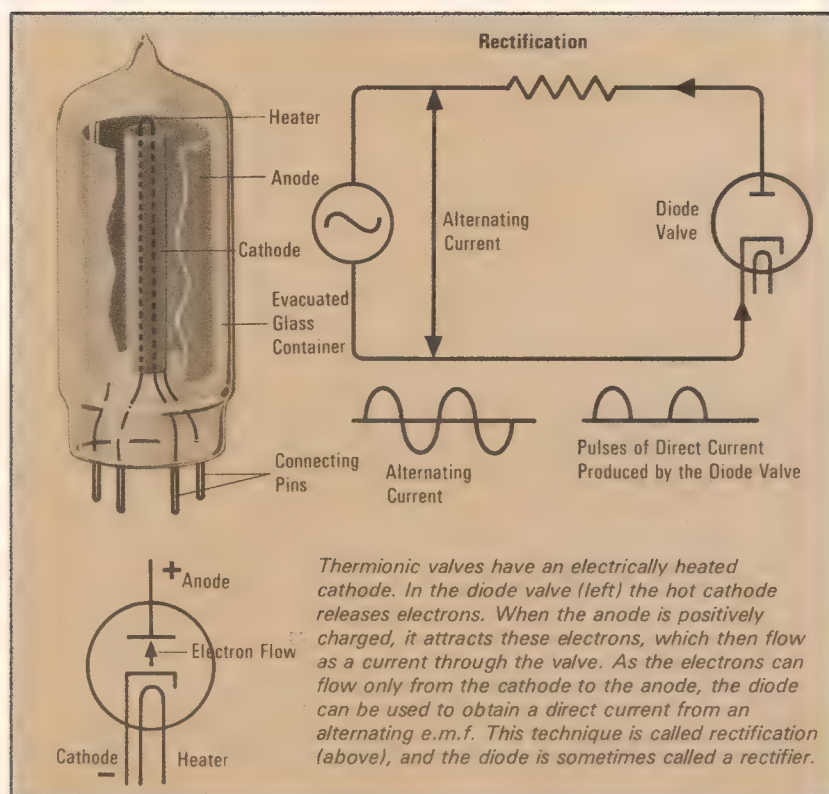
Above: At much lower pressure, the gas ceases to glow. Invisible cathode rays (electrons) travel from the cathode to the anode. This is a simple form of cathode-ray tube. Stray electrons striking the sides of the tube produce a green fluorescent glow.



Above: In an X-ray tube, the high positive charge on the anode attracts the electrons at high speed. The interaction between the electrons and the atoms in the anode causes X-rays to be emitted. These leave the tube and can be used to form an X-ray picture on a sheet of photographic film.

Below: The oscilloscope is an instrument for displaying electric signals in graph form. Varying electric fields deflect the fine electron beam emitted by the heated cathode, making it trace out a pattern on the fluorescent screen. The screen glows where the beam strikes it, thus producing a visible trace.





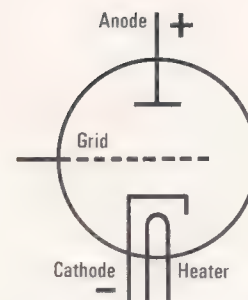
History of Electronics

In the 1800s many scientists experimented with the strange effects produced by electricity in air at low pressure. A bright glow was produced when a potential difference of several thousand volts was applied across two electrodes in a partial vacuum. And, at an extremely low pressure, the air itself did not glow, but the glass tube containing it gave off faint green light. In 1859, Julius Pflücker suggested that the glass glowed because it was struck by rays emitted by the cathode (negative electrode). For he had discovered that an object placed between the cathode and the glass caused a shadow on the glass. Other scientists confirmed Pflücker's theory and showed that the stream of cathode rays could be deflected by placing a magnet near the tube. In 1895, Wilhelm Röntgen investigated reports by other experimenters that cathode rays seemed able to penetrate thin metal. Röntgen found that, in fact, different rays were formed when cathode rays struck a metal object in the tube. The new rays became known as X-rays. They could pass through the air, and through solid objects, and would fog photographic plates—just as if the plates had been exposed to light. By passing X-rays through his wife's hand onto a photographic plate, Röntgen produced the first X-ray photograph.

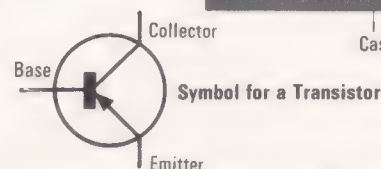
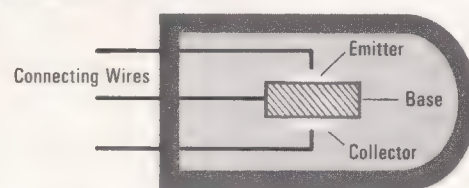
The development of wireless equipment from the late 1880s led to the invention of *electronic valves*. Ambrose Fleming's *diode valve* of 1904 passed current one way only and could be used to detect radio signals. Lee de Forest's *triode valve*, invented in 1906, could also amplify signals. When reliable amplifying valves became available, other scientists began to realize the great importance of de Forest's invention. So much became possible, now that weak signals could be amplified. In the technological explosion that followed came sensitive radio receivers, television, radio telescopes, radar, electronic computers, and many other inventions.

The next major advance in electronics came in 1948 with the development of the *transistor* by Shockly, Bardeen, and Brattain. Like the valve, the transistor can amplify signals. But the transistor has the advantage of being much smaller and more robust. It is also more efficient because, unlike a valve, it has no glowing filament to consume power.

Transistors are made from materials called *semiconductors*, whose electrical properties lie between those of conductors and insulators. Further research and development has led to the production of smaller and smaller *integrated circuits*—complex arrangements of transistors and other components. An integrated circuit the size of this letter 'o' could contain hundreds of electronic components. Because transistors and integrated circuits consist only of solid material (unlike valves), they are known as *solid-state* devices.



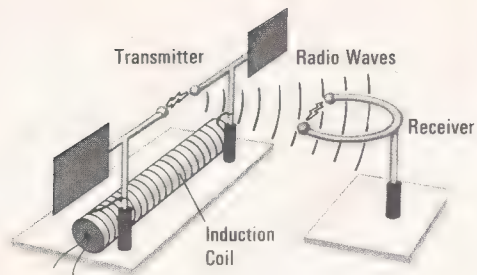
Above: The triode valve has a wire mesh, called a grid, between the cathode and the anode. The charge applied to the grid affects the electron flow from cathode to anode. For example, a high negative charge on the grid causes it to repel any approaching electrons (also negative), so that none reach the anode. A small, varying voltage applied between grid and cathode causes larger corresponding variations in the electron flow through the valve and associated components. In this way, the triode amplifies the signal applied to the grid.



Above: A transistor is formed from crystals of semiconductor material, such as germanium or silicon. A slice of crystal is treated with certain impurities to form three regions with distinct electrical properties. These regions are called the emitter, base, and collector. A small, changing current flowing between the base and the emitter causes large variations in the current flowing between the emitter and collector. In this way the transistor can amplify signals.

Below: A modern electronic circuit can be made so small that it can be fitted on to a silicon chip which will pass through the eye of a needle. This circuit contains over 120 components, and the 'rope' is 40 gauge sewing cotton.





Above: Heinrich Hertz (1857-1894) used an induction coil (a type of transformer) to produce a high voltage. This caused a spark to jump between the knobs of the transmitter, and radio waves were emitted. The waves were picked up by the receiving ring and caused a small spark to jump across the gap.

Right: Guglielmo Marconi (1874-1937), after hearing of the experiments of Hertz, devised various forms of apparatus to convey messages using electromagnetic waves. He used very high aerials, which greatly increased the distance of communication.



Radio and Television

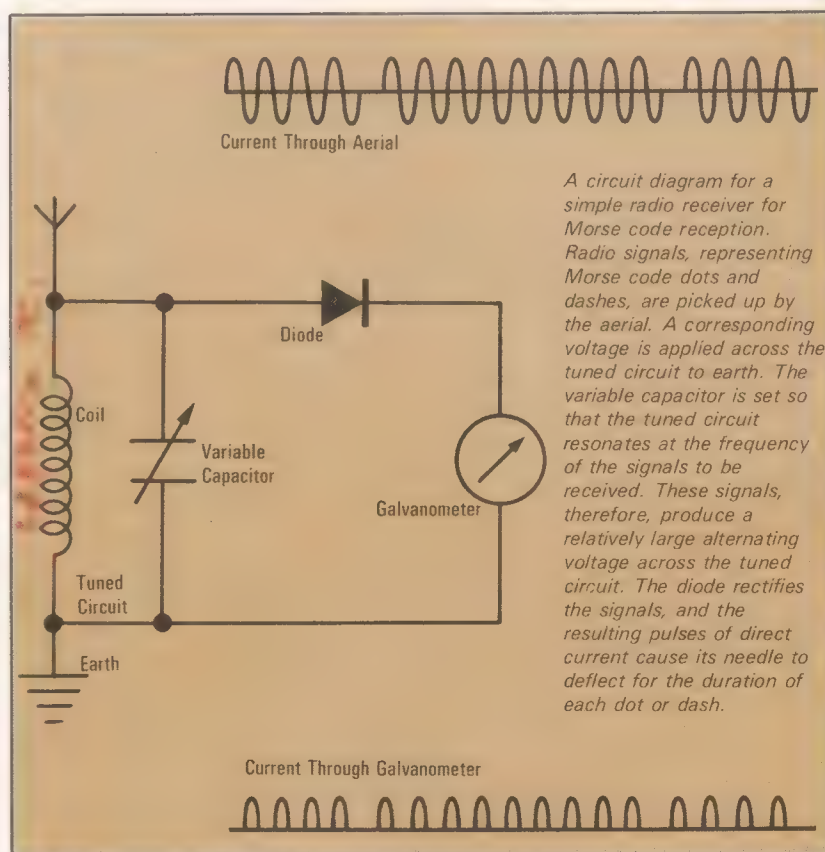
Radio

Radio was predicted before it was invented. In 1865, the Scottish scientist James Clerk Maxwell stated that it should be possible to make an alternating current send electromagnetic waves through the air. In 1887, an experiment by Heinrich Hertz proved Maxwell right. Hertz used a high alternating voltage to produce sparks. Each time a spark occurred, a pulse of current passed through the circuit, and electromagnetic waves were radiated. The waves produced a spark across the gap in a nearby brass ring. This was the first deliberate transmission and detection of radio signals. Like light, X-rays, and all other forms of electromagnetic radiation, radio waves travel at 300 million metres per second.

Hertz could detect the radio waves only when his receiver—the brass ring—was close to the transmitting apparatus. But other scientists, fascinated by the prospects of sending messages from one place to another without using connecting wires, soon developed much more sensitive detection systems. The most sensitive of the early detectors was the *coherer*. It consisted of a glass tube containing metal filings between a pair of electrodes. Radio waves made the filings cohere, or stick together, allowing a current to pass between the electrodes. In one type of radio receiver, the coherer was connected in series with a battery and electric bell. When radio waves were received, the filings would clump together, completing the circuit and making the bell ring.

The Italian Guglielmo Marconi developed practical systems for radio communications in the 1890s. Marconi achieved great success and, in 1901, his radio station in Cornwall transmitted a signal that Marconi received in Newfoundland.

By this time, tuned circuits, consisting of a coil and capacitor, were being used to tune in, or select, radio signals picked up by a wire aerial (see page 128). But one great problem remained. The coherer, although sensitive, was not reliable in operation. Sir John Ambrose Fleming solved the problem in 1904, when he introduced the diode (two-electrode) valve for detecting radio signals. This valve was a practical application of the *Edison effect*, discovered by Thomas Edison in 1883. While





As a direct result of early radio communications, Harvey Crippen, the wife-poisoner, and Ethel Le Neve (disguised as a boy) were arrested on board ship in 1910 as they tried to escape across the Atlantic. The captain of the ship was able to radio a message to the police in London, telling them that the couple were on board. This is believed to be the first occasion that radio played a part in crime detection.

experimenting with electric lamps, Edison had discovered that a small current would flow between the glowing filament and a separate metal electrode placed in the evacuated bulb. The important feature of the diode was that it passed current in one direction only. An alternating current produced in an aerial by a received radio signal could not be detected on a galvanometer. For the needle could not follow the rapidly alternating current, and the average value of the current was zero (see page 126). But the diode could be used to *rectify* the signals—convert them to pulses of direct current. And the pulses could deflect a galvanometer because, as the current flowed in one direction only, its average value was no longer zero.

In 1906, it was found that some crystals act as rectifiers when a fine wire is placed in them. So, like the diode valve, the crystal diode could be used to detect radio signals. But a much more important discovery was made in the same year. In the United States, Lee de Forest found how to make a valve amplify. He simply placed a fine wire grid between the electrodes of a diode, thus making it into a *triode*, or three-electrode valve. Small voltage variations applied to the grid cause large, corresponding variations in the current passing through the valve. De Forest's invention was vital to the further development of radio and other branches of electronics.

Early radio communication was carried out by transmitting bursts of radio waves in Morse code. Then, it was realized that, if the strength, or amplitude, of a radio signal could be *modulated* (made to vary) according to the strength of a sound signal produced by a microphone, it would be possible to transmit speech. By the end of World War I (1914–18), radiotelephony (voice communication by radio) was common. In a typical transmitter, a valve circuit called an *oscillator* generated radio signals. Other valves amplified the speech signals and produced a corresponding

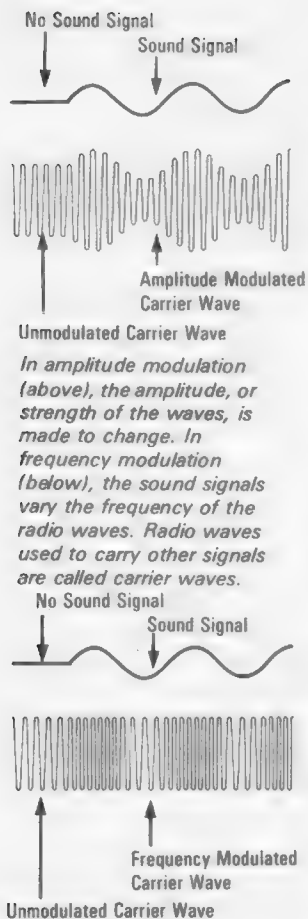
varying voltage. This was used to alter the strength of the radio signals produced by the oscillator. In the receiver, a diode or triode detector demodulated the received signal, separating from it the required sound component. This was then reproduced on headphones or, after amplification, on a loudspeaker.

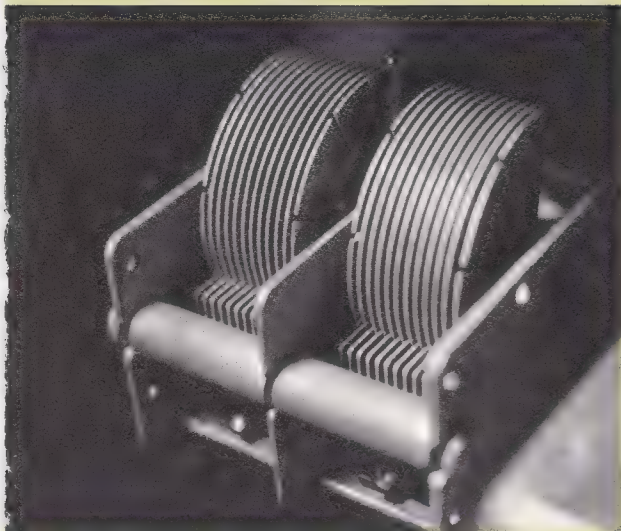
Regular radio broadcasting to inform and entertain the general public started in the 1920s. At first, most people listened on headphones connected to simple crystal sets, for receivers of this kind were simple to operate and required no power supply. But gradually, as the number of radio stations increased, much more sensitive and selective valve receivers, with several tuned circuits and amplifying stages, became popular. In the 1930s, a new system for sound transmission was introduced. Instead of the sound signals making the strength of the radio waves (amplitude modulation) it modulated their frequency instead (frequency modulation). As the receiver had to detect frequency changes, not amplitude changes, it did not reproduce any amplitude changes caused by electrical interference. As a result, almost all background noise was eliminated, giving excellent reception.

A more recent development has been the introduction of stereophonic broadcasting. Two signals, corresponding to the sound heard by the two ears, are combined and transmitted together. In the receiver, the signals are detected, separated, amplified, and then reproduced on two loudspeakers, placed some distance apart. Stereophonic broadcasting increases realism, because the sounds appear to come from various directions, as in real life.

Television

The discovery of the photoelectric effect (see page 114) in the 1870s led many scientists to attempt to transmit pictures by wire. A lens could be used to form an image of a scene, and an array of photoelectric cells could be used to convert the brightness of each part of the image into corresponding voltages. These voltages would then be used to reproduce a picture of the scene, perhaps by illuminating an array of tiny electric lamps. Unfortunately, the power produced by the cells was too small to illuminate a lamp, so the system was impracticable. The development of the amplifying triode valve in the early 1900s made such a system possible. But it was inconvenient to use hundreds of pairs of wires to carry the vision signals from the array of photoelectric cells. To avoid this, a technique called *scanning* was used. The image to be transmitted was scanned, or sampled, bit by bit. Signals corresponding to the brightness of each element were transmitted, one after another, along a single pair of wires. In England in the 1920s, John Logie Baird used a rotating scanning disc in a system designed to transmit silhouettes. The disc had been invented by the German



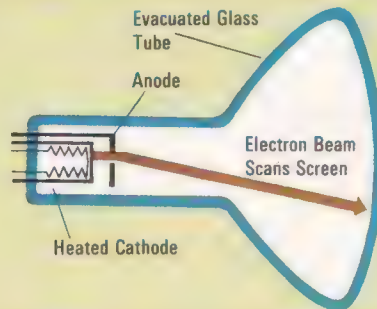
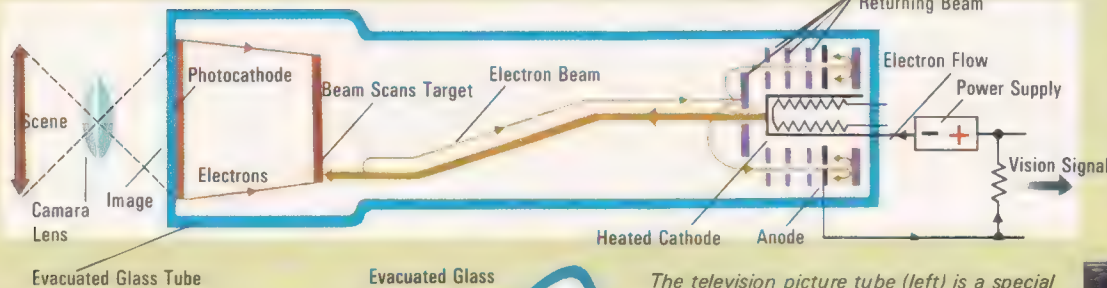


A variable capacitor (sometimes called a condenser) is used to select or 'tune into' a radio station that is broadcasting on a particular frequency. When the plates of the capacitor are in the correct relative positions, the tuned circuit resonates to the frequency of the selected radio station.

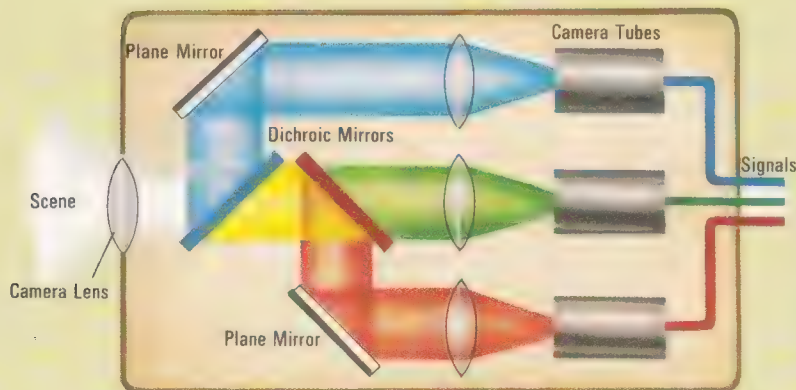


Left: A television camera in use. The lens of the camera forms an image of the scene. From this image, the camera tube, a special form of cathode-ray tube, produces a vision signal. This signal can be displayed as a replica of the scene on a television picture tube.

Below left: In the image-orthicon camera tube, the camera lens forms an image of the scene on a light sensitive cathode. This emits a pattern of electrons. These electrons strike the target and dislodge electrons from it, leaving it with a charge pattern, or 'electrical image'. The electron beam from the cathode sweeps quickly across the target, line after line. At each point on the target, the beam deposits just enough electrons to replace those previously dislodged. The returning beam therefore varies in strength, according to the charge pattern on the target. This varying beam is used to form the television signal.

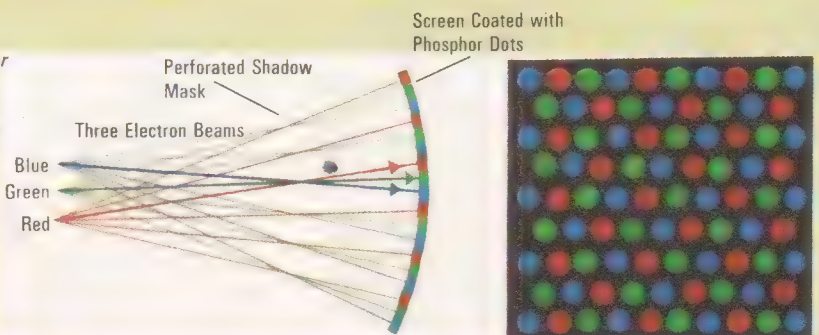


The television picture tube (left) is a special form of cathode-ray tube that converts the vision signal into an image of the televised scene. The vision signal controls the strength of the electron beam as it scans the fluorescent screen, line by line. The screen glows according to the strength of the moving beam. Hundreds of lines of varying brightness together form a completed picture. Some of these lines can be seen in this highly magnified photograph (right) of part of a black and white television screen.



Left: A colour television camera contains tinted mirrors, called dichroic mirrors, which split up the light from the scene into blue, green, and red colour components. The images are then scanned by three image-orthicon camera tubes, and three separate vision signals are produced. These are then combined in a special way, so that they can be sent along a single cable, and transmitted like a black and white signal.

Right: In a colour television receiver, the three colour components are separated out from the combined vision signal. Each colour component controls the strength of an electron beam. The three beams scan the screen, which is coated with minute dots of chemicals called phosphors in a particular arrangement (far right). These glow blue, green, or red when struck by electrons. The perforated mask ensures that each beam strikes only one type of phosphor. As a result, three superimposed colour images are formed on the screen. We see these images as a single, full colour picture of the scene being televised.





scientist Paul Nipkow in 1884. An image of the scene was formed on the rotating disc. Holes in the disc passed, one at a time, across the image, exposing a photoelectric cell behind the disc to each part of the image in return. Baird amplified the signals produced by the cell and used them to vary the brightness of a small neon lamp. A second scanning disc rotated in front of the lamp. As each hole in the disc passed quickly across the flickering lamp, it appeared to the eye to form a line of varying brightness. A complete image was built up in this way from a series of lines, scanned quickly, one after another. A mechanical scanning system was used for the first regular experimental television broadcasts, which were made in New York in 1928. The vision signals were made to modulate radio waves, in the same way as speech signals were transmitted by radio. Several other television stations started to broadcast using mechanical scanning systems. But these were gradually replaced by the more reliable electronic scanning system, which had been developed in the United States by the Russian physicist Vladimir Zworykin. In this system, modified cathode-ray tubes were used in the camera and receiver. In the camera tube, an electron

The studio set for a television play. The camera and microphones are placed so that they can follow the action on the set. The microphone is mounted on a boom above the action, just out of view of the camera. The camera is mounted on a 'dolly' that has silent, smooth-running wheels. The stand is designed so that the operator can achieve a variety of different angles and positions relative to the action. The camera operator and other members of the floor crew are equipped with earphones, through which they receive instructions from the control room.

beam was made to scan an image of the scene and produce a vision signal. In the receiver's picture tube, the image was reconstructed by an electron beam scanning a fluorescent screen. This is the system used today.

The most common type of black-and-white camera tube used in broadcasting is the image-orthicon. An image of the scene is formed on a layer of photoelectric material, causing it to emit electrons in a pattern corresponding to the light values in the scene. These electrons strike a glass disc called a target plate, knocking electrons from it and leaving it with a pattern of positive charges. Rapidly changing magnetic fields make the electron beam in the tube scan the 'electrical image' on the target, line by line. The beam deposits just enough electrons (negative charges) to cancel the positive charge at each point on the target. So the electron beam leaving the target varies in strength according to the number of electrons 'lost' to the target. The variations in beam strength are amplified to form the vision signal.

In a television picture tube, the vision signal is made to vary the strength of an electron beam as it scans a screen of fluorescent material. The screen glows according to the strength of the beam at each point. Therefore, as the beam strength varies, the brightness of the line it traces out varies too. The brightness pattern thus formed on the screen corresponds to the brightness pattern of the image formed on the camera tube. So the picture tube reproduces the original scene.

Although the electron beam in the picture tube strikes only one point on the screen at a time, it moves so rapidly that, to the eye, it appears as if the whole screen is glowing continuously.

In order to reproduce the scene correctly, the beam in the picture tube must scan exactly in time with the beam in the camera tube. For this reason, timing signals called synchronizing pulses are added to the transmitted vision signal. In the receiver, these pulses control the scanning of the electron beam.

Colour Television

In one type of colour television camera, optical devices form three separate images containing the red, green, and blue colour components of the scene. The three coloured images are scanned by camera tubes to form three vision signals. These signals are then combined in a special way that enables them to be separated again, when this is required. The combined signal is transmitted in the normal way.

In the receiver, the colour components are separated and fed to a picture with three electron beams. These scan the tube together, forming red, green, and blue images respectively. Each colour signal controls the strength of the corresponding beam, so three superimposed colour images are formed. We see these images as a single, full-colour replica of the scene being televised.



A ghost image is the result of reflection of the television signal from tall buildings in the neighbourhood of the television receiver. The main signal reaches the aerial first. A reflected signal reaches the aerial a fraction of a second later. The result is that a second, weaker image is formed on the screen, slightly displaced from the main image.

Computers

BINARY CODE

The binary system of numbers uses zeros and ones only. The system uses a 'yes/no' principle—a one indicates 'yes' and a zero indicates 'no'. The binary system can therefore be used to show the presence or absence of certain decimal numbers. In practice, these numbers are 1, 2, 4, 8, 16, 32, 64, and so on, as shown below.

64	32	16	8	4	2	1	
0	0	0	0	0	0	1	= 1
0	0	0	0	0	1	0	= 2
0	0	0	0	1	0	0	= 4
0	0	0	1	0	0	0	= 8
0	0	1	0	0	0	0	= 16
0	1	0	0	0	0	0	= 32
1	0	0	0	0	0	0	= 64

The binary number 10010101 therefore equals the decimal number 149 ($128 + 16 + 4 + 1$).

Binary numbers can be punched onto tape, which can then be fed into a computer. On punched tape a hole indicates a one, or 'yes', and no hole indicates a zero, or 'no'. On the piece of punched tape shown below the following numbers have been punched:

1011	= 11
100	= 4
1100	= 12
111	= 7
1001	= 9
1101	= 13



Digital Computers

Computers are tools that enable us to calculate quickly and conveniently. Digital computers perform calculations involving *counting*. When ancient man began to acquire possessions, he needed a counting system. To start with he used his fingers. But large numbers were difficult to manage in this way, and counting systems that used groups of units and tens were devised. These led to the development of the abacus. In the early abacus, pebbles were placed in columns between lines marked on a table or other smooth surface. Even today, the abacus is still the most common calculating machine in the world. In the modern abacus, beads are slid along wires to represent counts of units, tens, hundreds, thousands, and so on.

In 1642, a French mathematician called Blaise Pascal invented a new kind of calculating machine. Pascal's machine used a system of toothed wheels, each with ten teeth. Numbers could be added by turning the wheels by an appropriate number of teeth. The advantage of this machine was that numbers could be carried from one place of decimals to the next. When the units wheel passed the ninth tooth, the tens wheel was automatically moved on by one tooth.

By the 1800s, many other mechanical calculators had been invented. Some worked well. Others, although theoretically sound, failed because their delicate mechanisms could not be manufactured with sufficient accuracy. The most outstanding designer in this field was Charles Babbage, a mathematics professor at Cambridge University, England. In 1832, Babbage invented the first automatic general purpose computer. It was called an *analytical engine*, and it had many features that are used in modern electronic computers. But, like so many other machines invented at that time, it was too complicated to be built reliably. So Babbage never received the recognition he deserved.

More than one century elapsed before the first successful automatic general purpose

computer was built. This machine was completed in 1944 by Howard Aiken of Harvard University, Massachusetts. Aiken's calculator contained counter wheels, electric motors to turn them, electromagnets, and many other parts—over 750,000 in all. The machine gave useful service until the late 1950s. But, even while it was being completed, a much more versatile tool was being developed—the electronic computer.

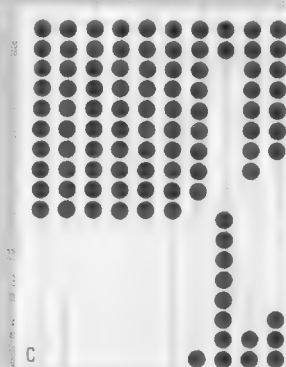
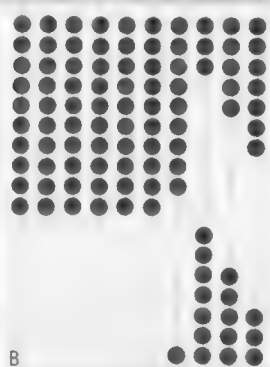
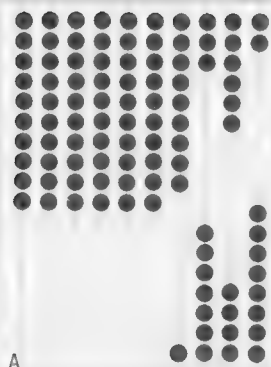
Electronic Digital Computers

ENIAC (Electronic Numerical Integrator and Calculator) was designed by electrical engineer J. Presper Eckert and physicist John Mauchly. Completed in 1946, ENIAC was the first automatic electronic digital computer. More than 150,000 watts of electricity were needed to power the circuits, which contained about 18,000 valves, 1500 relays (switches operated by electromagnets), and hundreds of thousands of other components. Numbers were fed into the machine on punched cards. The coded holes in the cards were used to form pulses of electricity, which were then fed to electronic circuits that carried out the calculations. Numbers could be added together at the rate of 5,000 per second—breathhtaking at the time, although very slow by modern standards.

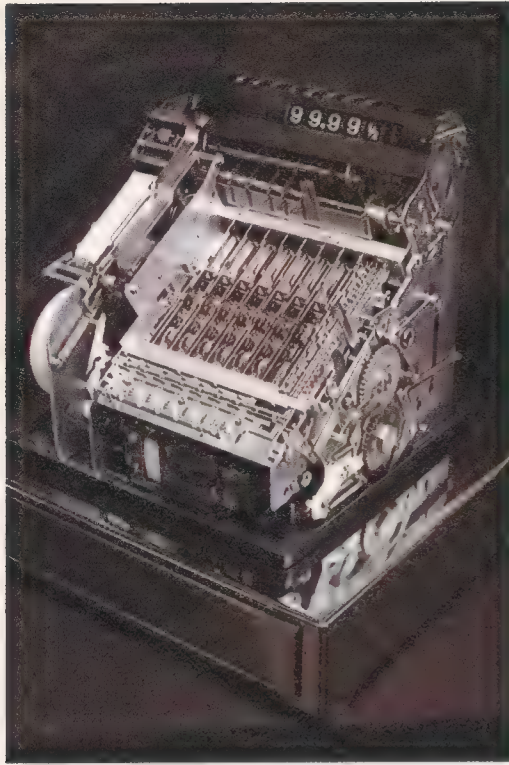
For most purposes, valves were considered to be extremely reliable. But ENIAC had so many of them that failures were frequent. In later computers, the valve was replaced by much more reliable, efficient, and smaller solid-state devices—first the transistor, and then the integrated circuit.

Modern electronic digital computers handle numbers in *binary code*. This is because the binary system uses only two digits: 0 and 1. These digits can be conveniently represented in the computer by the absence (0) or presence (1) of electrical pulses, holes in a card, or magnetic spots on a tape or disc.

Before it can be used to solve a problem, the computer must be given instructions about what to do. The instructions, which form the *program*, are held in coded form by magnetic rings called *cores*. These form the computer's *store*, or memory. The *data* (figures to be used in the calculation) are fed into the computer from an *input device*. For example, the data may be fed straight into the computer from a keyboard machine operated like a typewriter.



On this abacus, the numbers 1748 and 75 are being added together. First, 1748 is set on the abacus (A). The number 5 is then added to the units column (B). But this would give 13 in the units column, so 1 is added to the tens column, leaving 3 in units column. Finally, the number 7 is added to the tens column. (C) Again, this would give 12 in this column, so 1 is added to the hundreds column, leaving 2 in the tens column. The final result is therefore 1823.



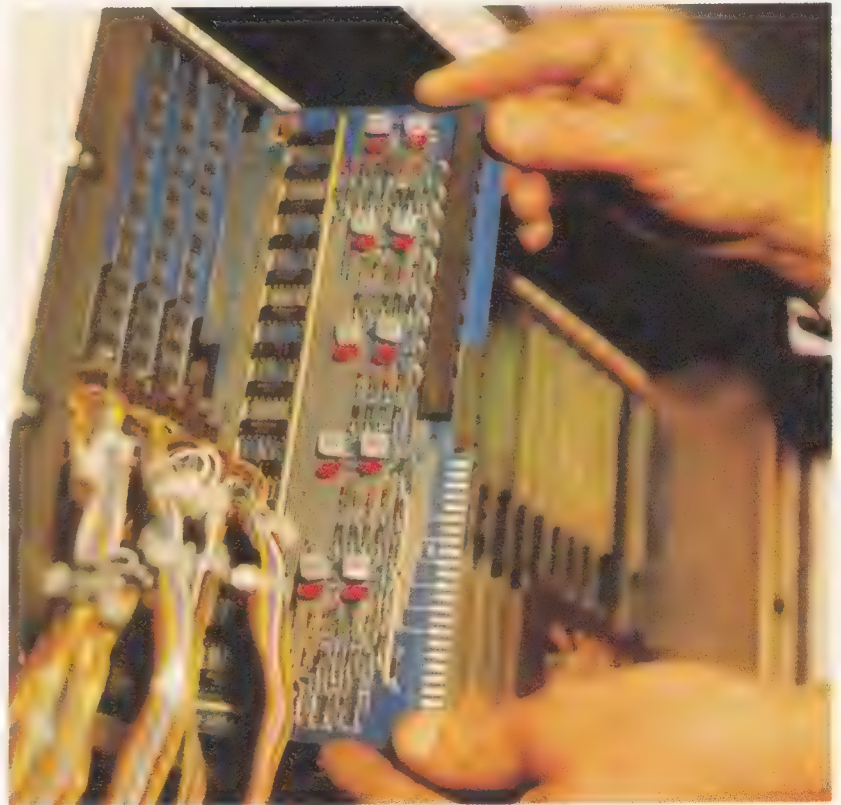
Left: A cash register is a mechanical digital computer. It contains wheels that turn to certain positions to represent numbers. Addition is accomplished by counting the number of turns that a wheel makes. Modern cash registers are usually electrically operated.

Below: A printed circuit board being inserted into a computer. The computer is built up using many such boards, which can easily be removed. This aids the location and repair of faults.

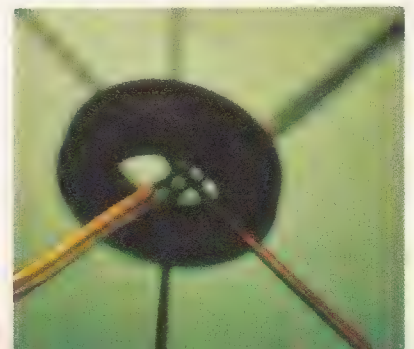
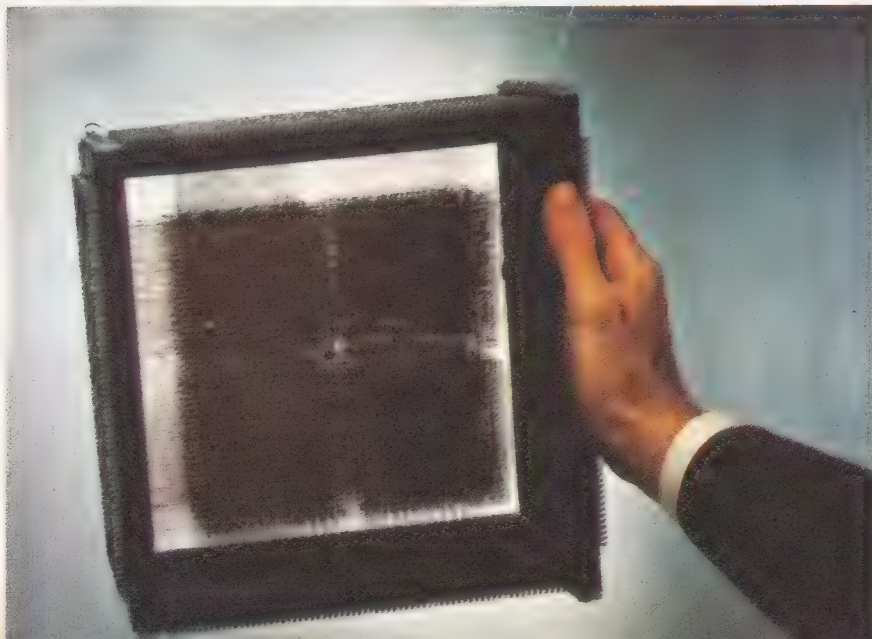
Or a tape containing the information in code may be played into the computer. Electronic circuits in the *processor*, or arithmetic unit, carry out the calculation, the whole sequence of operations being directed by the *control unit*. The results of the calculations are obtained on *output devices*, which include cathode-ray-tube screens and high-speed printers. Recorders, such as magnetic or paper tape punches are used as output devices when the results have to be stored for future use.

Analog Computers

Analog computers calculate by *measuring* quantities similar, or *analogous*, to the quantities being calculated. The mercury thermometer, for example, is a simple analog computer for calculating temperature. As the temperature varies up or down, the height of the mercury column varies in a similar manner. The height of the column, as measured on a scale marked in degrees, gives the temperature.



A computer memory core store (left) contains thousands of small ferrite cores. Each core can be magnetized in either a clockwise direction or an anticlockwise direction by current-carrying wires passing through the core (below). When magnetized one way, the core registers a binary 1. When magnetized the other way, it registers a binary 0.



The World of Sound





Living with Sound

We live our lives surrounded by sound. Even at the quietest moments, some sound—the creak of a chair or the sigh of the wind—can be heard. People who have to shout against the roar of aircraft or the clatter of machines probably often wish for silence. But many people find working and living in total silence very uncomfortable. A little distraction helps them to concentrate and relieve solitude. Sound has to be controlled to make life pleasant. Very loud noise is more than a nuisance; it can cause pain and damage hearing.

Sound is made when a surface vibrates. You can easily demonstrate this by twanging a ruler on a table top or by stretching a rubber band and plucking it. As the surface moves to and fro, it sets up a sound wave in the air. As it pushes into the air, the air molecules are forced together and a region of high pressure forms. This region is called a *compression*. Then the surface moves away and the molecules move apart, forming a low pressure region or a *rarefaction*. As the surface vibrates, alternate compressions and rarefactions are set up in the air and they travel out from the surface to produce a sound wave. The molecules do not move with the wave, but vibrate to and fro in time with the surface.

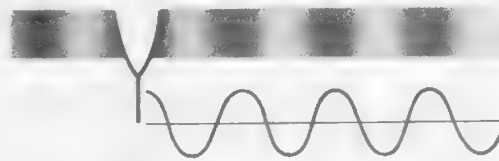
The wave moves through the air at a set speed, but the speed depends on the temperature of the air. At freezing point, the speed of sound is 331 metres per second. At normal temperatures, the speed of sound is about 340 metres per second. Light travels

Above: The ancient Greek open-air amphitheatre at Epidauros, designed by Polyclitus in 340 B.C. Such theatres had excellent acoustics. They were designed so that every member of the audience was in a direct line from the stage, and could hear everything that was said.

much faster, and the difference in the speeds of sound and light is just great enough to be detectable over a long distance—but not so far that the sound disappears. At a cricket or baseball match, the batsman or batter can be seen to strike the ball before the sound of the hit reaches the spectator.

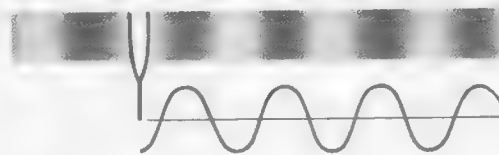
Sound will travel through any medium where there are molecules to move, but it travels faster in more elastic substances because the vibrations are passed on more quickly. Liquids and solids are more elastic than gases; sound travels at 1483 metres per second through pure water and at nearly 6000 metres per second through steel. A vacuum will not carry sound waves, simply because it is devoid of molecules. Astronauts on the airless surface of the Moon cannot therefore talk to each other normally but have to converse by radio.

Sound is produced by vibration of any kind. Vibration of the vocal cords in the throat produces speech and song; in television sets, radios and gramophones, a loudspeaker cone vibrates to produce sound; in musical instruments, a string, reed or skin may vibrate; as you walk over some gravel, the tiny stones jostle each other to produce a scrunch. The sound waves then move away in all directions through the air until they meet another surface. This surface is then set vibrating by the pressure variations in the air. The surface vibrates at exactly the same rate as the original object producing the sound. If the receiving surface is the drum of the ear, we hear the sound. If it is a hard surface, such as a wall or cliff, it will reflect the sound, producing an echo as the sound comes back to the ear. But soft surfaces, such as curtains, absorb the sound because its energy is soaked up by the fibres of the material.

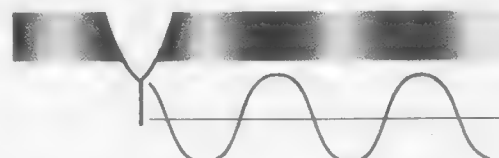


Sound waves, alternate compressions and rarefactions of air, are formed when a tuning fork vibrates.

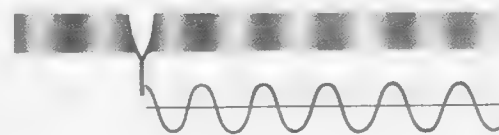
As the prongs of the tuning fork move outwards, a compression is formed.



As the prongs move inwards, a rarefaction forms.



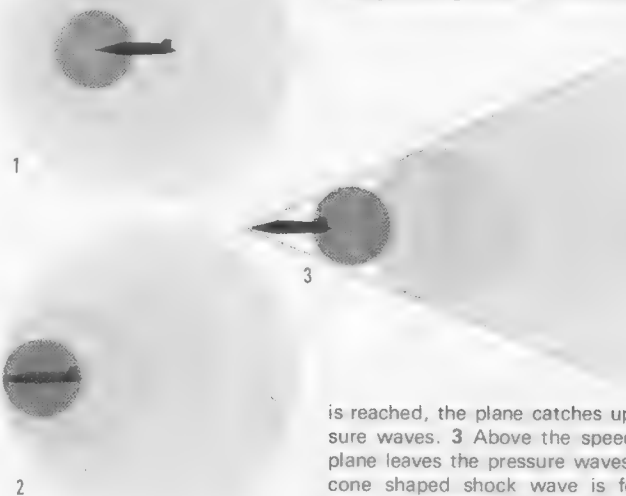
If the fork is struck harder, the compressions are greater, and the sound is louder.



If a smaller fork is struck, the vibration (frequency) is more rapid and the wavelength is shorter; a higher-pitched sound is heard.

SONIC BOOM

1 Below the speed of sound an aircraft flies inside a pattern of pressure waves caused by its passage through the air. 2 As the speed of sound



is reached, the plane catches up with the pressure waves. 3 Above the speed of sound the plane leaves the pressure waves behind, and a cone shaped shock wave is formed. As the shock wave passes it is heard as a dull boom.

Acoustics

These principles are considered when concert halls and recording studios are built. The study of controlling sound is called *acoustics*. It is important also in the design of vehicles and machines such as jet engines. A concert hall or studio must first of all be sealed off from all outside sounds. These sounds will travel through the framework of the building and through the floors and walls. The concert hall or studio has therefore to be wrapped in soft soundproofing materials to stop sound getting in.

Inside the hall or studio, the sound must not be allowed to escape. In fact, the amount of sound reflected from the walls—the amount of echo, or reverberation—is important to the sound of the music. Too little echo and it sounds dry and lifeless; too much echo, and the sound becomes 'muddy' and loses detail. Cathedrals produce huge amounts of echo from the stone walls; so much so that it is often difficult to make out what a priest is saying. Recording studios possess little echo because echo is added to the recording artificially. But concert halls have to be designed very carefully to give just the right amount of echo to the sound coming from the stage. This depends on the size and shape of the hall as well as the materials used in its construction.

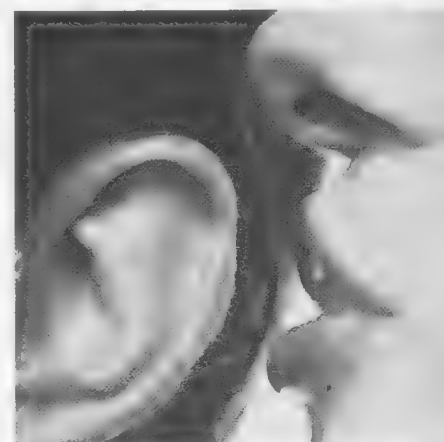
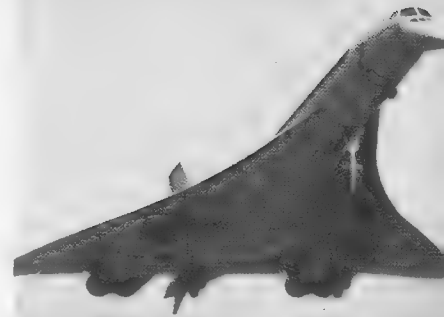
Pitch and Intensity

A compression in a sound wave is a maximum of energy and a rarefaction is a minimum. The greater the energy difference between them—which occurs as a surface vibrates more widely—the greater the intensity of the sound and the louder it seems to us. The rate of vibration—the rate at which compressions or rarefactions pass—is called the frequency of the wave. The higher the frequency, the higher the pitch of the sound (the more treble it sounds). Frequency is related to wavelength (see page 84), and a higher-pitched sound has a shorter wavelength. These principles governing loudness and pitch can both be shown by twanging a ruler; if you push it harder, it vibrates more strongly and loudly, but if you shorten the part that is vibrating, it vibrates faster and the sound is higher.

Intensity is measured in decibels (dB). The scale is logarithmic so that an increase of 10 dB doubles the loudness, a sound 20 dB more intense is four times as loud, and so on. A sound of 0 dB is at the threshold of hearing but at 140 dB, sound begins to hurt. Frequency is measured in hertz (Hz) or cycles per second (cps). It is perceived differently from intensity, and a frequency twice as great as another sounds an octave higher; that is, twice as high.

We hear sounds of different frequency but the same intensity as differing in loudness. Our ears are most sensitive to sounds at about 2000 Hz—the C three octaves above middle C. This is why high-pitched sounds are most piercing to the ears. On either side, hearing falls away and sounds lower than 20 Hz and higher than 20,000 Hz are inaudible to humans.

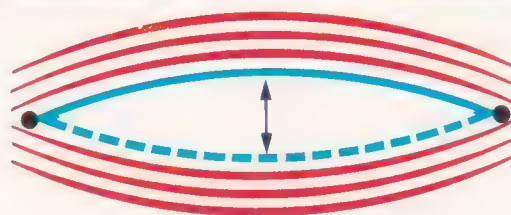
DECIBELS AT SOUND SOURCE



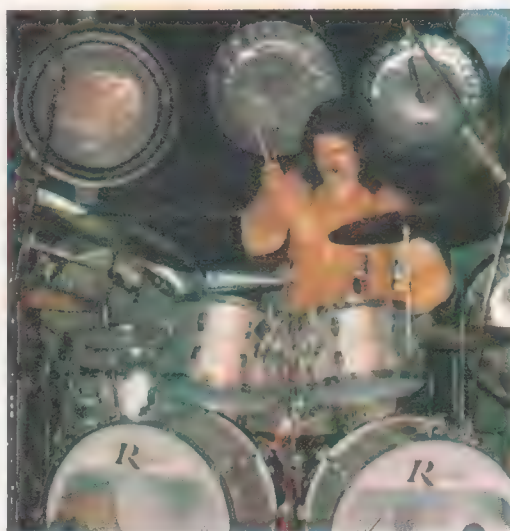
Musical Sounds

Why should one instrument sound so different from another? The obvious answer is because they are played in different ways—striking a drum is bound to sound different from bowing a violin or plucking a guitar. But we do not have to see an instrument to recognize it. There must be something about the sound itself that is different in each case. This quality is its *tone*.

Every instrument has a certain range of notes, though some notes are easier to get than others, as any one who has strived for a high note on a trumpet will know. Each of these notes is in fact made up of a whole series of notes. The ear usually hears only the pitch of the lowest note in the series because this is the loudest note. But sometimes it is possible to hear more than one of the series; if you listen carefully to the sound of a deep bell, you may hear that more than one note is sounding. These extra notes are called *harmonics*. Although they cannot usually each be heard, together they influence the kind of tone that is heard. A note in which the harmonics are strong sounds bright and strident; a note in which the harmonics are weak sounds pure and round. A tuning fork produces a



Drums (right) sound when a stick or mallet strikes the taut skin and sets it vibrating (above). The note may be changed by altering the tension of the skin.



Cymbals and gongs (right) are discs of metal set vibrating by striking with a stick or brush. They do not give a set note, though the larger the cymbal or gong, the deeper its sound.



A solid metal bar will produce a note when struck (above). The xylophone (right) has a set of metal bars that are struck by mallets to produce a particular range of notes.

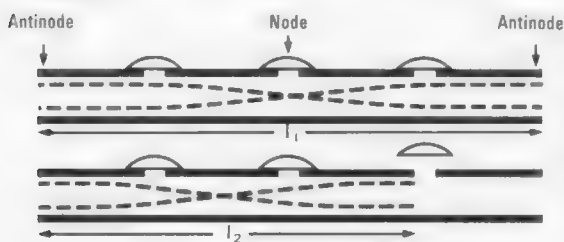




String instruments include the violin (above left), viola, cello, double bass, guitar, banjo, piano (above), and harpsichord. The string is made to vibrate (left) by plucking it with the fingers or a plectrum, stroking it with a bow, or striking it with a hammer. The piano has a set of strings, one or more for each note. They are set vibrating by striking them with hammers operated by keys. The harpsichord is similar, but the strings are plucked mechanically.



A woodwind instrument has a column of air that is set vibrating by blowing across a hole in the instrument, as in the flute (above) or piccolo, or by blowing into a mouthpiece containing a vibrating reed, as in the clarinet, oboe, bassoon and saxophone. The note is changed by opening and closing holes along the side of the instrument, thus altering the length of the vibrating air column (below).



Brass instruments contain an air column set vibrating by the action of the lips in the mouthpiece. They include the trumpet, cornet, trombone, horn (opposite, above) and tuba. Notes are changed by pressing valves to open sections of tubing — or, in the trombone, by moving a slide to alter the length of the air column. For each finger or slide position, a certain range of notes can be obtained by blowing at different pressures.

The pipe organ (opposite, below) contains a set of pipes each similar to a flute, but without holes. Each one produces one note and sounds when air is blown down it by a motor. The blowing action is operated by a keyboard.

pure note without harmonics; the sound of a gong on the other hand is full of harmonics.

Harmonics can be sounded individually by carefully fingering on the guitar and other string instruments, and by blowing harder on brass instruments. They occur because every surface that vibrates to make a sound—whether it is the skin of a drum, a taut string or the air column of a wind instrument—vibrates in several ways at once. The surface vibrates as a whole, and also as two halves each at twice the frequency, and as three thirds each at three times the frequency, and so on. These multiples of the basic or fundamental frequency give the harmonics.

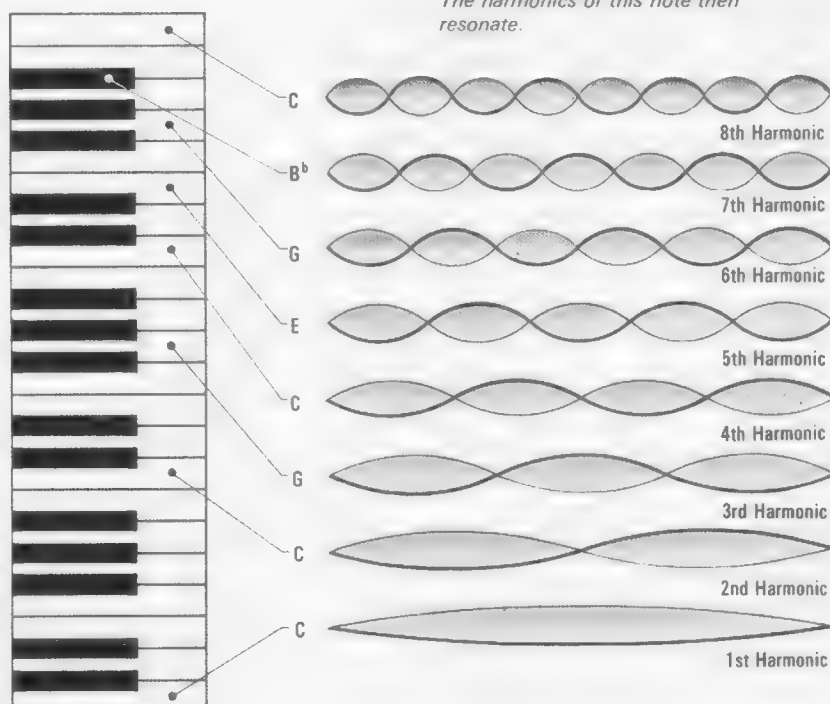


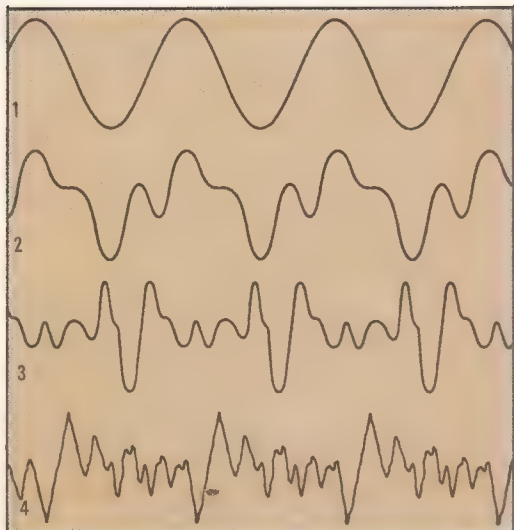
Electric instruments produce sounds by a combination of old and new methods. The electric guitar (above) and bass guitar have sets of strings that are plucked in much the same way as the Spanish guitar. But a pick-up placed beneath the strings converts the vibration of each string into an electric signal. This signal goes to an amplifier and loudspeaker to produce the sound. The tone and volume are varied by controls on the amplifier. The shape of the instrument is not important for the sound and can take almost any form. The electric piano is similar, having a set of vibrating rods that are struck by hammers connected to the keyboard. At the end of each rod is a pick-up.



Above: An electronic synthesizer. Electronic instruments contain no sound producing mechanism at all. In instruments such as the electronic organ and synthesizer, electric signals are generated by electronic circuits and fed to an amplifier and loudspeaker. The keyboard and controls act like switches in selecting certain signals. In both electric and electronic instruments, foot pedals are often used to give control over the sound while playing with both hands.

A piano string vibrates to give a series of harmonics. They can be heard by holding down the keys shown without sounding them and then striking the bottom key sharply (in this case, a C). The harmonics of this note then resonate.





The wave form of a sound is related to its tone. A tuning fork (1) produces a regular curve, showing that its sound consists of a single frequency and is pure and mellow. As harmonics are added, the sound becomes brighter and harsher and the wave form gets more jagged, as with the flute (2), oboe (3) and violin (4).

RESONANCE

An instrument can be made to sound without playing it. If a note reaches it that is in tune with any part of the instrument free to vibrate, then the instrument itself will sound as well. Open the piano and press down the loud pedal so that the strings are free to vibrate. Then sing loudly into the piano, while still pressing the pedal. When you stop singing, you will hear the piano ringing with sound; the strings have been set vibrating by the sound of your voice. Many instruments make use of this effect, which is called resonance. The body of a violin or guitar resonates with the sound of the strings and amplifies the sound.

The presence of harmonics in a sound affects its wave form. The wave form of a note is a representation of its energy change with time. A pure note without harmonics has a wave form resembling a gentle curve (see the illustration on page 138). It is not necessary to draw graphs to see waveforms. An electronic instrument called an *oscilloscope* displays wave forms on a screen.

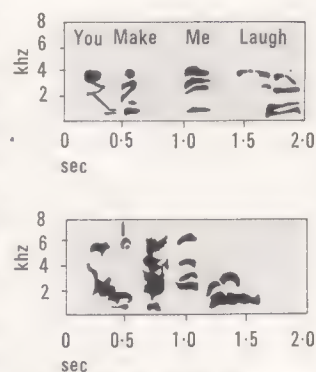
If a pure note has harmonics imposed on it, the wave form of each harmonic alters the wave form of the resulting sound. The shape of the resulting wave form depends on the proportions of harmonics in the sound. A sound with few harmonics has a gently curving wave form, resulting from an even vibration in the instrument. The flute is an example, and it has a round, mellow sound. If the vibration is uneven, the harmonics are strong and the wave form is jagged; a harsher sound is produced, as in the violin and oboe. A *synthesizer* can make a wide range of sounds by producing several pure wave forms electronically and then combining them in different ways to give various wave forms.

Another quality that is essential to recognizing instruments is the start of a sound. The way in which the note begins to sound once the player has started to play is very important. A hard sound such as a drum beat begins very

rapidly, whereas an electric guitar played with a wa-wa pedal produces notes that start slowly. These starting sounds are called *transients* and they help us to recognize instruments with similar tones. If a recording of an oboe has its transients altered, it can sound like an organ, for example. Our recognition of words in speech comes from the different transient of each consonant as well as the different tone of each vowel sound.

A musical sound also possesses a certain pitch as well as tone and transient, but the pitch may be varied in many ways. In wind instruments, the column of air vibrating in the instrument is shortened to give higher notes. In string instruments, the length of string that vibrates is shortened by pressing it against a fingerboard. In timpani, the vibrating skin is tightened to give a higher note. Other instruments possess a set of sound-producing objects to give different notes. The violin family and guitar have strings of varying weight, the heavier strings giving lower notes, and the harp and piano have strings or wires of different length as well as weight. The xylophone and similar tuned percussion instruments have bars of different size, the smaller bars producing higher notes.

Some instruments, such as drums and cymbals, do not give a note of definite pitch but instead produce noise. Noise is sound covering a wide frequency range without any particular frequency dominating the others.

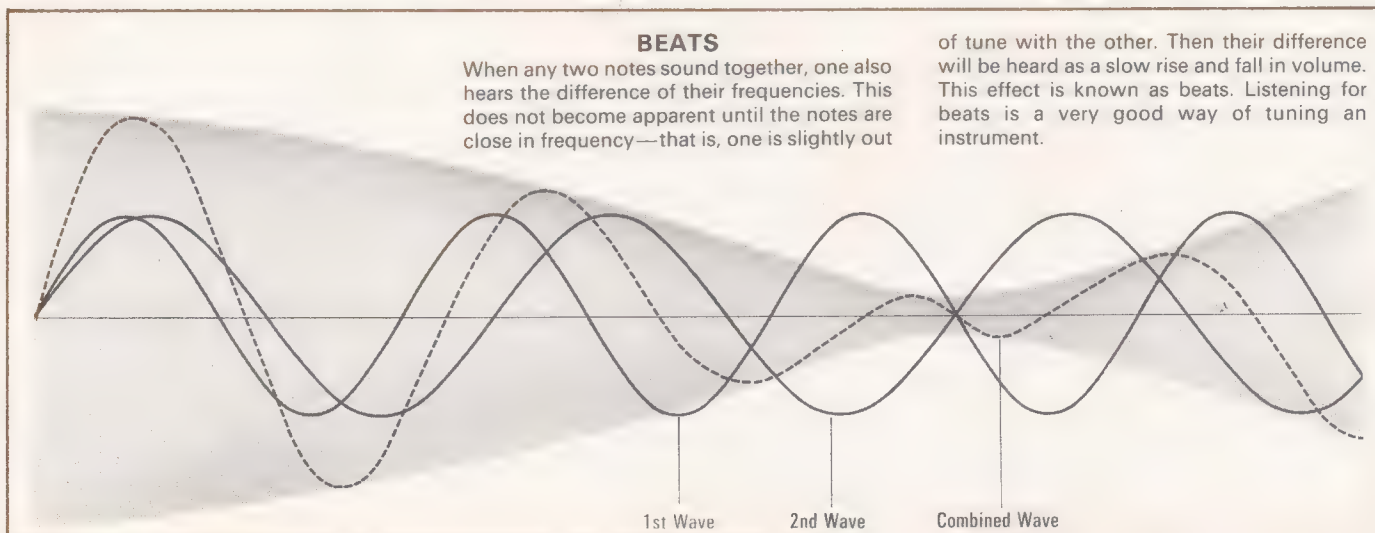


Two spectrograms that show the similarity of the speech of a human (top) and a mynah bird (bottom).

BEATS

When any two notes sound together, one also hears the difference of their frequencies. This does not become apparent until the notes are close in frequency—that is, one is slightly out

of tune with the other. Then their difference will be heard as a slow rise and fall in volume. This effect is known as beats. Listening for beats is a very good way of tuning an instrument.





Silent Sound

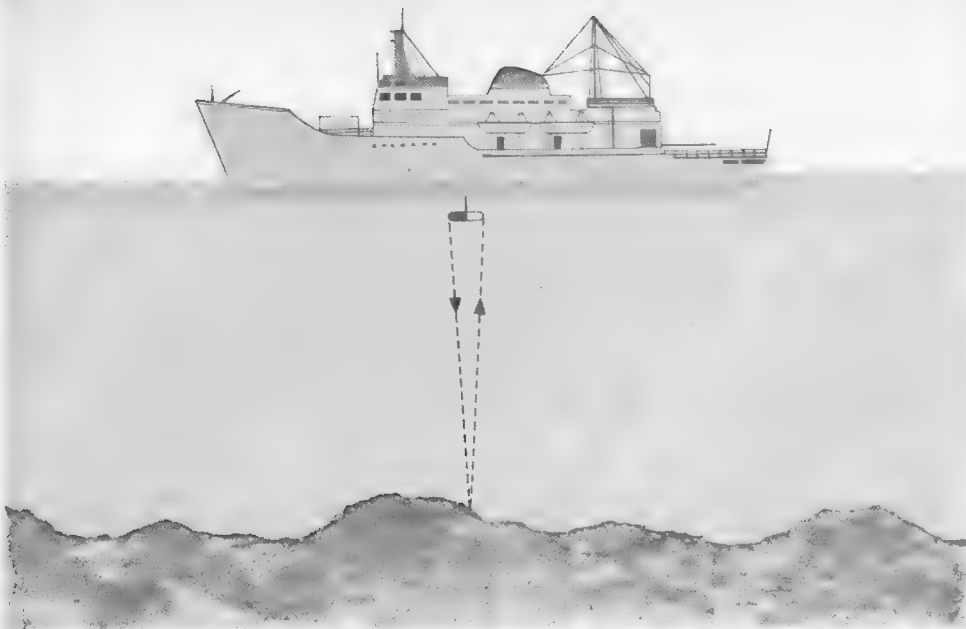
Above: The greater horseshoe bat in flight. Bats use ultrasound to locate objects in the dark. They emit very high-pitched squeaks that are inaudible to the human ear. Objects in the path of a bat cause the sounds to be reflected back to the bat's ears, which are large in proportion to the rest of its body.

It seldom, if ever, occurs to us that a whole world of sound exists that we cannot hear. We believe that we have good hearing, but we would not say the same of a mosquito or a snake. The hearing of these animals is limited to a range of about 200 Hz up to 800 Hz, just two octaves in the middle of the piano. This happens to be the sound range of the buzz of the mosquito's wings and its limited perception of sound helps one mosquito to recognize another—an essential aid to mating. The snake's hearing is limited by its primitive ears and it probably senses the approach of other creatures by vibrations through the ground.

But several animals would consider us partially deaf; the bat, for example, has a hearing range six times that of man and so does the dolphin. They can hear and produce sounds up to 120,000 Hz in frequency, whereas man's hearing stops at 20,000 Hz. This limit decreases as we grow older and the ear becomes less sensitive. Bats produce squeaks at about the upper limit of human hearing, which is why children can often hear bats and adults cannot. This silent sound is known as *ultrasonic* sound or *ultrasound*, and even though we cannot hear it, we can

make good use of it. The word 'ultrasonic' must not be confused with 'supersonic'. Ultrasonic means higher (in frequency) than the sound heard by man; supersonic means faster than the speed of sound—supersonic aircraft fly faster than sound.

The main use of ultrasonics, both in the animal and the human world, is to detect distance. In principle, it is used in the same way as radar. A pulse of ultrasound—a squeak from an animal or a bleep from an ultrasonic source—is reflected by an object and returns to its source, like an echo. From the time it takes for the pulse to travel to and from the object, the distance of the object can be accurately calculated. Bats fly unerringly through the dark in this way, continually giving out squeaks of ultrasound and picking up their echoes. Dolphins navigate through the water in the same way. They do not perform calculations of course, but somehow sense the shapes around them from the sound picture they hear. You could in fact determine whether you were in a very large building such as a cathedral or in an average-sized room while blindfolded, simply by clapping your hands sharply. A cathedral would produce a distinct echo and the room would



not. But echo location in animals is far more precise than this. One reason is that the very short wavelengths of ultrasound give a 'sharper' picture of objects.

Sonar, or echo-sounding, is one of the main uses that man makes of ultrasound. Sonar stands for 'sound navigation and ranging' and it is a method of detecting distances underwater. Pulses of ultrasound are produced by an echo-sounder fixed beneath a ship. The return time of the echoes is shown graphically on a chart. This chart traces out a profile of the sea bed below, and it will also show up shoals of fish and wrecked ships or submerged buildings. In wartime, sonar has proved invaluable for detecting submarines.

In industry, a similar technique can be used to detect the existence and location of flaws in solid objects. The flaw sends back an echo of ultrasound just as a fish does when an echo-sounder passes overhead. Machines that must perform faultlessly can be examined in this way; parts for nuclear reactors are subjected to ultrasound tests, for example. Ultrasound is also valuable in medicine for examining the interior of the body, particularly for examining unborn children. An ultrasound image of the baby can be made simply and easily without the danger that using X-rays might cause.

Echo location like that used by bats has been developed for blind people. The blind person carries an ultrasonic emitter and detector, and the ultrasound echoes received from nearby objects are turned into sound signals at normal frequencies and heard through headphones. The method works well for detecting obstacles, but it does not enable the blind person to 'see' in any detail.

These echo location techniques employ ultrasound at low power. At high power, ultrasound has a disruptive effect on anything it meets. It causes heating, produces streams of bubbles in liquids, shatters large molecules and pits the surface of metals. However, it does have uses. High-power ultrasound can speed up chemical reactions, improve electroplating and remove grease and dirt from surfaces.

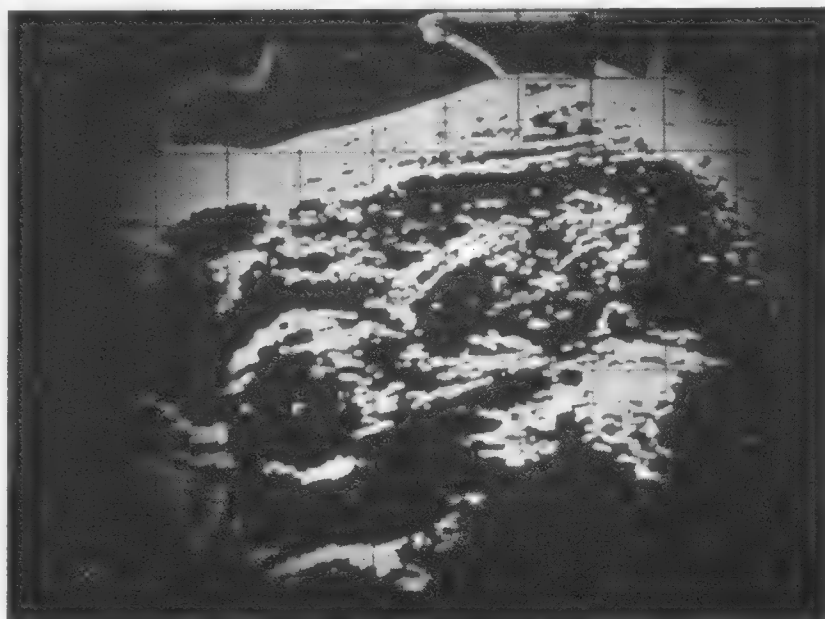
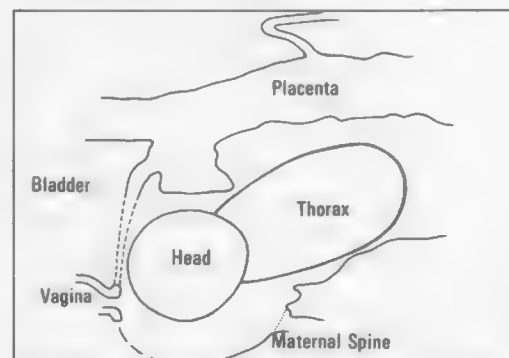
A survey ship uses sonar to map the bottom of the sea (above left). Sonic pulses are emitted by a transducer underneath the ship. These are reflected back and recorded as a trace (above right).



Infrasonics

Sound below the range of human hearing—that is, below 20 Hz—is known as *infrasound* or *infrasonic* sound and is as silent as ultrasound. Normally we do not notice it, but at high power, the sound waves become waves of high pressure in the air and can be felt. Tests have shown that high levels of infrasound produce nausea, dizziness and other physical effects. It is possible that a noisy car produces infrasound at levels that could affect the driver, and military scientists believe that a powerful infrasound transmitter could make an effective weapon.

Using ultrasonics, an 'echo picture' of an unborn baby can be obtained. The results generally have to be interpreted by experts. But the picture below clearly shows the head and thorax (upper part of the body) of the baby, together with the placenta, vagina and bladder of the mother.

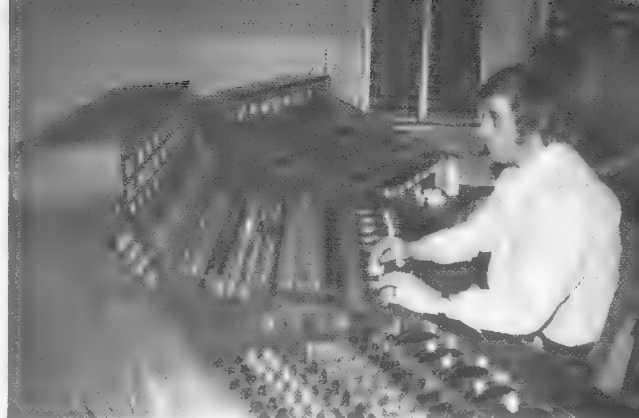




1

1. A recording session in a studio.
2. The music is recorded on tape, and is monitored by engineers in the control room. The desired tone, volume, and mixture of sounds is carefully maintained using an array of electronic controls. Before the recording session is over, the musicians may have recorded several 'takes'.

2



Recording Sound

Any system of sound recording is basically a system of energy conversion and storage. The physical sound itself cannot be captured and kept in a bottle for future use. It must be changed into another form of energy that is capable of storage, and then changed back again. But throughout all the changes, the wave form of the sound must be preserved as exactly as possible so that the recording will sound like the original sound.

Any device that changes energy from one form to another is called a *transducer*. In sound recording, transducers change sound into electricity and back again. A microphone produces an electric signal that varies in intensity in exactly the same way as the vibrations of the sound wave entering the microphone. The loudspeaker takes this electric signal, amplified in voltage but possessing the same variations in intensity, and the cone of the loudspeaker vibrates in step with the variations in the signal and sound is reproduced from the loudspeaker. But in between these two energy changes, the electric signal must be stored.

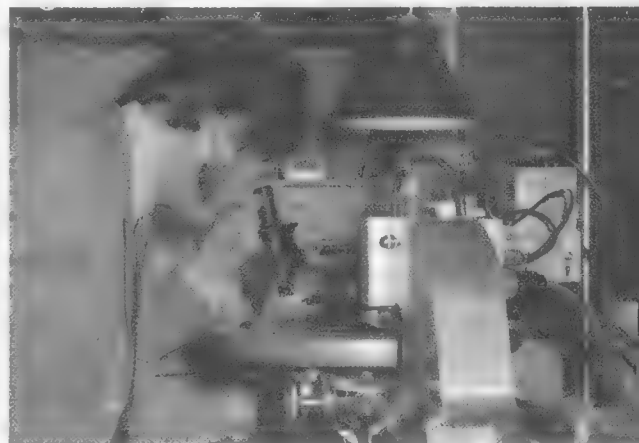
This can be done in three ways—on magnetic tape, on a gramophone record and on film—but magnetic recording is always used first. The reason for this is that magnetic tape is very easy to use and very flexible. It can easily be cut so that a piece of music may be recorded in sections, or 'takes', and the best takes put together later to make the record. The orchestra may also be divided up into several sections, each with its own microphones, and each section recorded on a separate part of the tape, called a *track*. Modern recording studios use as many as 24 tracks on tape 5 cm wide. Then a final tape is prepared in which the volume level and tone of each individual track is adjusted to give the best overall sound. Editing and multitrack recording usually improve the artistic and technical quality of the recording.

3. An editor selects the best parts of these 'takes', and splices them together to make a master tape. From the master tape a metal disc is cut (4). This consists of an aluminium base covered with a thin layer of cellulose material. After cutting, the disc is silvered in a silver nitrate solution. A master disc is then made by depositing a layer of nickel electrolytically on the cut disc. The nickel layer is then removed, cleaned and inspected. From this master disc, a working positive is then made. This is done by first coating the master with a film of potassium dichromate, and then depositing nickel electrolytically on the surface. The positive nickel layer, once removed, is virtually a metal record that can be played on a record player. Finally, matrices are made from the positive by the same electrolytic process. A plastic record is pressed from a matrix. The edges are trimmed, and the record inspected (5).

3



4



5



6

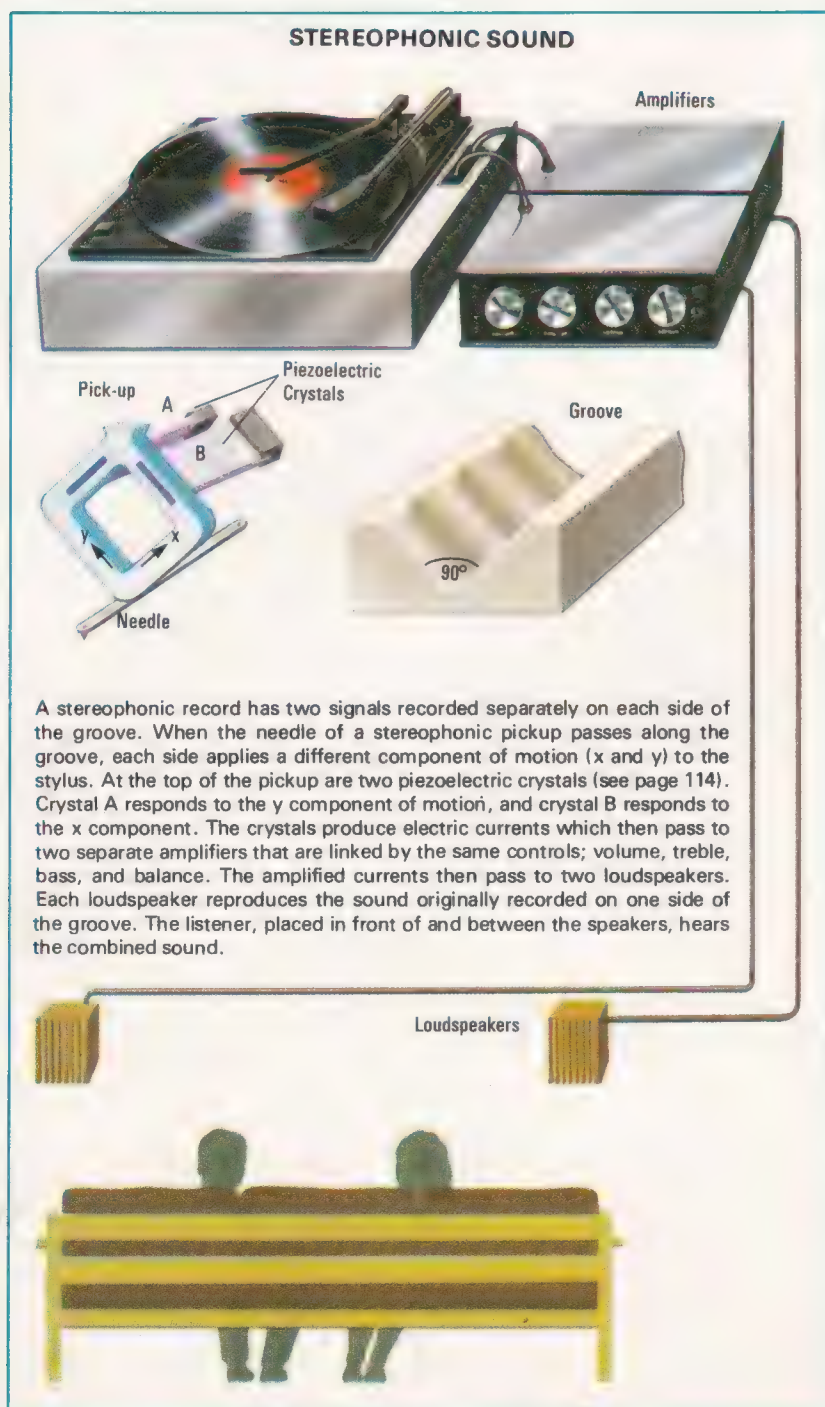


6. Cassette tapes are manufactured by duplicating them from the original master tape.

In a tape recorder, the electric signal from the microphone produces a varying magnetic field that causes a magnetic pattern to form on the tape as it passes the recording head. On playback, the recorded tape passes the playback head and the magnetic pattern induces a varying electric signal in the head. This signal goes to an amplifier and loudspeaker and the original sound is heard. Cassette tapes are direct copies of the master tape produced in the recording studio.

A gramophone record is made from the master tape. The master is played back in a tape recorder and the varying signal produced goes to a mechanical cutter that cuts a groove in a blank disc. From this master disc, copies of records are made and sold in the shops. The curves in the walls of the groove correspond to the vibrations of the original sound. A

The finished records and cassettes are packaged and sold.



stylus is placed in the groove and vibrates as the groove passes. This vibration is changed back into a varying electric signal in the gramophone pick-up—using the same energy conversion techniques as those of the microphone—and the signal goes to an amplifier and speaker to produce sound.

In film recording, the signal from the master tape causes a light to vary in brightness as the film passes it. A varying optical pattern is produced in the film. When the film is shown, a light shines through the pattern onto a photoelectric cell. As the pattern passes, a varying electric signal is produced in the cell and this then goes to an amplifier and loudspeaker.

Realistic Sound

Modern recording studios can record sound very accurately. But if the result is heard through one speaker, it comes from one direction only, whereas in real life, sound comes to us from all directions. *Stereophonic* sound aims to make recorded sound more realistic. The sound is spread out between two speakers, creating an illusion of the instruments being spread out in front of the listener. This is done by dividing the original sound into two and sending each half to a separate speaker. This is simply done in tape recording by using two tracks instead of one. In a gramophone record, the two walls of the groove each carry a different signal, and the pick-up easily separates them. But two speakers still do not give total realism, for sound comes from all around us in real life. This is true even in a concert hall, because echoes bounce off the walls and reach the ears from all directions. *Quadraphonic* recording aims to capture sound from all directions by having four speakers placed around the listener. The sound is recorded in four quarters and each quarter goes to a separate speaker. Quadraphonic sound is easy to capture on tape by having four tracks playing at once. But disc recording is not so simple. The four signals have to be placed one over the other in the walls of the groove and then an electronic decoder has to separate them from the signal produced by the pick-up. Ways of doing this vary and no standard has yet been reached by the recording industry. However, quadraphonic cassettes may well be the recording medium of the future.

Molecules in Motion

The motion of molecules gives rise to heat — and to cold. Heat is one of the most important forms of energy, and is put to great use by man. Here an engineer cools some piston linings before inserting them in an engine block. On insertion, the linings warm and expand, fitting them tightly in place.



Heat and Temperature

Heat, like so many things in life, is something that we cannot do without but also something of which we can have too much. A human being or any animal is a delicate balance of energy conversions. Too much heat—or too little—upsets the balance and puts life in danger. The amount of heat that reaches the Earth from the Sun is enough to support life over most of the Earth's surface. But no life exists without protection at the Poles; it is so cold that there is not enough heat energy to maintain the energy balance.

But, cold though the polar regions are, they do possess heat. Heat is a form of kinetic energy called *thermal energy*, and it exists in the motion of the molecules of a substance. The hotter an object is, the faster its molecules move (see pages 68–71). If we examined the molecules of a piece of rock at the Poles, we would find that its molecules were vibrating, though not as rapidly as those in a similar piece from the tropics, where it is much warmer. If we could cool the rock more and more, its molecules would vibrate more and more slowly and eventually stop moving. The rock would have no heat left at all and it would be as cold as it could possibly be. This is in fact very cold indeed: 273.16°C below freezing or -273.16°C . This temperature is known as *absolute zero*. It can never be quite reached, and so everything possesses a certain amount of heat.

Heat is produced by converting another source of energy into heat. Chemical reactions between the substances in the food we eat produce heat that keeps the body warm. Chemical reactions are also responsible for the heat of a fire. As the fuel burns, it combines with oxygen in the air, giving out heat as it does so. Electrical energy is changed into heat in an electric fire; the electrons moving through the wire collide with the metal molecules in the wire and increase their motion. Friction produces heat; when a moving surface or medium meets a still one, the molecules are speeded up in both, increasing their heat. Nuclear energy also produces heat; when atoms break apart, they fly out at great speed and increase the motion of any molecules they meet.

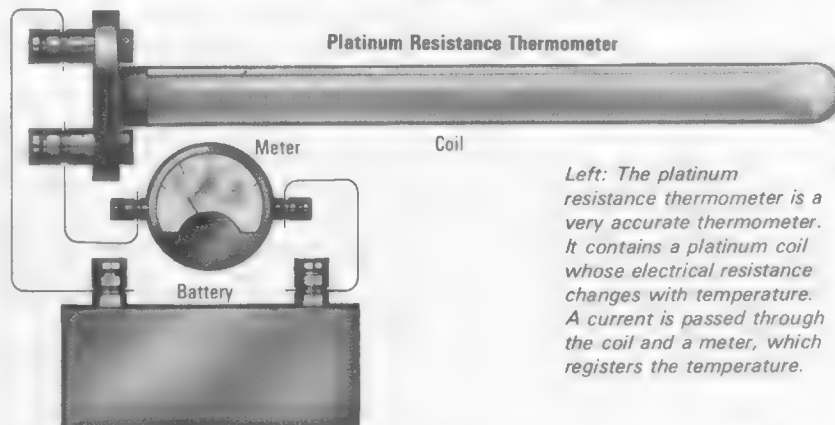
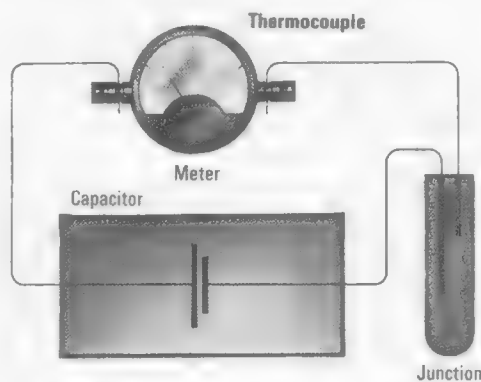
Heat and Temperature

It is important to realize that the temperature of anything does not measure the amount of heat that it possesses. Temperature is a measure of the degree of motion of the

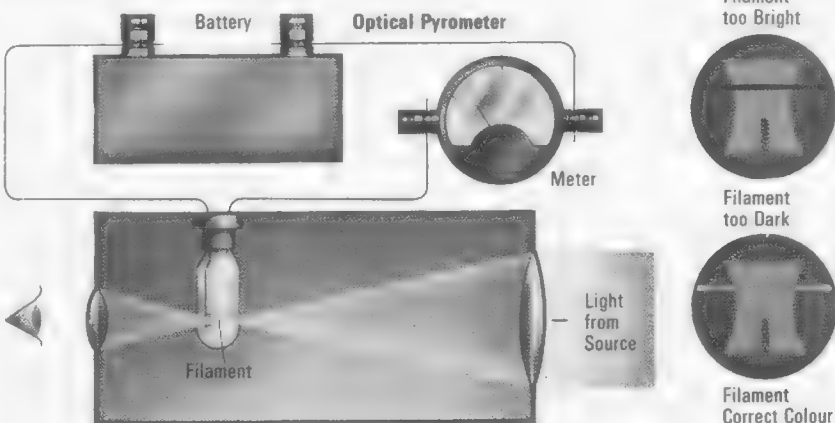
CONVERTING TEMPERATURES

To change Fahrenheit to Celsius (Centigrade), subtract 32 and multiply by $5/9$. For example, $68^{\circ}\text{F} = 20^{\circ}\text{C}$ ($68 - 32 = 36$; $36 \times 5/9 = 20$). To change Celsius to Fahrenheit, multiply by $9/5$ and add 32. For example, $10^{\circ}\text{C} = 50^{\circ}\text{F}$ ($10 \times 9/5 = 18$; $18 + 32 = 50$). To change Celsius to Kelvin, add 273.16; to change Kelvin to Celsius, subtract 273.16. In practice, whole numbers are often used and the 0.16 of a degree is dropped.

Below: The thermocouple is an electrical thermometer. A junction of two dissimilar metals produces an electric current when heated. This current goes to a meter that registers the temperature.



Below: The optical pyrometer measures the colour of light coming from a red-hot or white-hot source to find its temperature. This is done by comparing the colour of a filament heated by an electric current to the colour of the source. When the filament seems neither brighter nor darker than the source (right), the meter is read to find the temperature of the source.



Clinical Thermometer

Above: The clinical thermometer, like ordinary thermometers, works by expansion. It has a bulb containing mercury that expands along a narrow bore in a calibrated glass tube as the temperature increases. The clinical thermometer contains a constriction which prevents the level of the mercury falling immediately the thermometer has been removed from the patient's mouth to be read. Ordinary thermometers often contain coloured alcohol instead of mercury. These glass thermometers have a limited range.

Other thermometers include the gas thermometer which works on the principle that a rise in temperature causes an increase in pressure of a gas kept at constant volume, and the bimetallic thermometer which contains a strip of two metals that expand at different rates, causing the strip to bend when heated and move a needle over a dial.

Left: The platinum resistance thermometer is a very accurate thermometer. It contains a platinum coil whose electrical resistance changes with temperature. A current is passed through the coil and a meter, which registers the temperature.

molecules. A hot object has faster-moving molecules than a cold object. The amount of heat is related to the mass of an object as well as its temperature. A large mass of a substance at a low temperature could have a greater amount of heat than a small mass of the same substance at a high temperature.

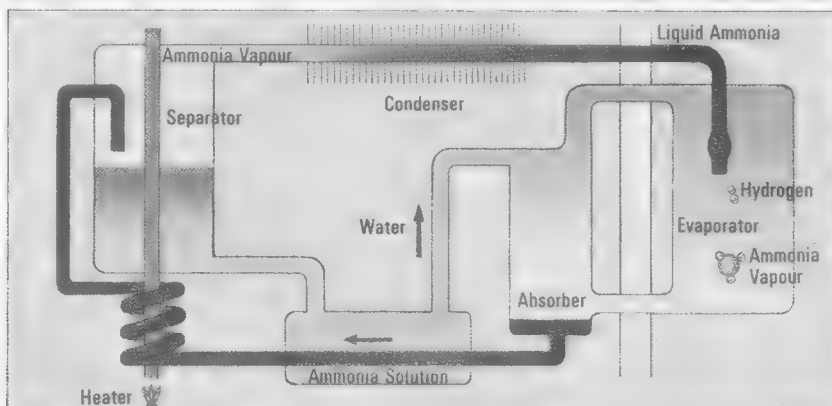
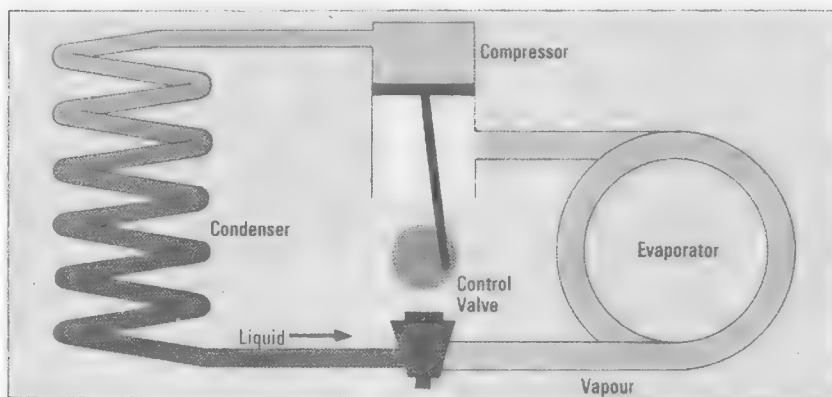
Several temperature scales have been devised. The Centigrade scale places the freezing point of water at 0°C and the boiling point at 100°C . It is also known as the Celsius scale after the Swedish physicist Anders Celsius who first proposed the scale in 1742 (though he suggested that freezing point be 100° and boiling point 0° , an odd decision that was soon reversed). Temperatures below freezing, which often occur in winter, are shown as negative or minus figures in the Celsius scale. To avoid this, the Dutch physicist Gabriel Fahrenheit had earlier proposed the Fahrenheit scale, in which the freezing point of water is 32°F and boiling point is 212°F . In 1848, the British physicist Lord Kelvin pointed out that the logical starting point of any temperature scale is absolute zero. This temperature should be 0° and all other temperatures should be measured from it in degrees equal in magnitude to degrees Celsius. This scale, called the Kelvin scale or Absolute scale, is now used in science and the SI unit of temperature is called the kelvin (K). Thus absolute zero is 0K , the freezing point of water is 273.16K and the boiling point of water is 373.16K .

Heat is energy and it is measured in joules (J). The amount of heat in an object depends on its mass and its temperature. It takes twice as much heat to raise the same mass



Checking the temperature inside a furnace with an optical pyrometer.

of a substance by twice the temperature (in kelvins), or to raise twice the mass of substance by the same temperature. But the final temperature depends on its specific heat capacity. A piece of copper will gain 50K in temperature when it receives the same amount of heat that produces a rise of only 5K in the same mass of water. Copper therefore has a specific heat capacity ten times that of water. Specific heat capacity is measured by giving a known mass of a substance a known amount of heat and measuring its rise in temperature. In SI units, it is expressed as the number of joules of energy required to give a mass of 1 kilogram of the substance a rise in temperature of 1K .



THE RANGE OF TEMPERATURE

The range of temperatures that are to be found in the Universe is enormous — from as much as 20 million kelvins (K) at the centres of stars to near absolute zero (0K) in outer space. But all other temperatures are very near the lower end of such a scale. The Sun's surface has a temperature of 6000K and iron melts at 1812K . Paper catches fire at 557K and water boils at 373K . The highest recorded temperature on Earth is 332K and the lowest 185K , while water freezes at 273K . Air liquefies at about 75K .

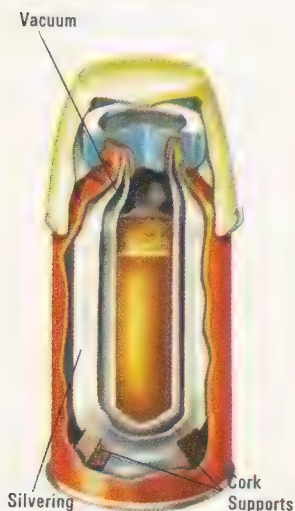
Left: Refrigerators work by taking heat from inside the cold compartment to the outside. This is done by cycling a volatile liquid from an evaporator placed inside the refrigerator, where it evaporates and takes up heat, to a condenser situated outside the refrigerator, where it condenses back to a liquid, giving out heat. In the electric refrigerator (top), an electric motor powers a compressor to pump the vapour from the evaporator to the condenser. In the gas refrigerator (bottom), ammonia liquid evaporates in the evaporator, in which hydrogen gas circulates. The ammonia vapour is then absorbed in water and flows to a heater. There the ammonia solution boils and the ammonia vapour rises to the condenser, being separated from the water in a separator. The water returns to the absorber.



The Flow of Heat

Above: The fennec fox lives in hot desert regions, where the temperature is so high that it cannot quickly rid itself of body heat. Its huge ears, however, allow the heat to be dispersed over a wide area. They act like cooling fins on an engine.

Below: A vacuum flask is designed to retain as much heat as possible. A vacuum exists between the double walls of the container to prevent heat loss by conduction, and the container is silvered to stop radiation loss. Finally, a large stopper is used to prevent heat escaping by convection. The flask also prevents heat getting in, if the contents are cold.



To be of any use, heat must somehow get from its source to the place where it is needed. Sometimes, these two locations are the same; the heat produced in a motor-car engine by the combustion of the fuel is immediately used to give power. But this is not always the case. The heat from a room heater or a coal fire has to spread throughout a room to be effective. The heat of a hot plate or gas flame on a cooker must get to the food in a saucepan if a hot meal is to be served. Heat flows in three different ways: by *conduction*, *convection* and *radiation*. Often, all three occur together. Heat flow is not always desirable and it is often necessary to stop heat transferring from a hotter to a colder body. Prevention of heat flow is called *insulation*.

Conduction

If you have ever burnt your fingers by picking up a hot pan from the cooker, you have experienced conduction. Conduction is the flow of heat through solids. If one end of a solid object is heated, the molecules at that end vibrate faster. They set their neighbouring molecules vibrating more, and these molecules jostle their neighbours and so on. Heat gradually moves through the object. Heat spreads from the hot plate or gas flame throughout the pan and, as you pick it up, heat flows into your fingertips and produces a sensation of burning. Similarly, if you pick up a piece of ice from the refrigerator, heat flows from your fingertips by conduction into the ice, and you sense cold.

Most metals are good conductors of heat, particularly copper and aluminium. Sauce-pans and kettles are mostly made of aluminium, which is also cheap and light. Wood, plastics

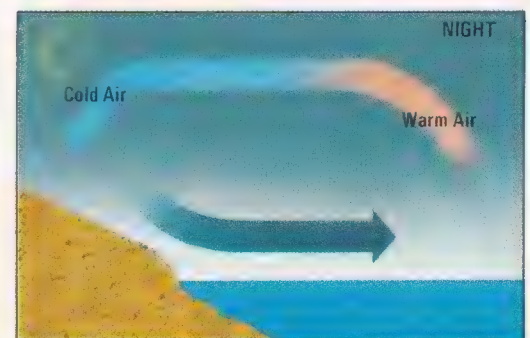
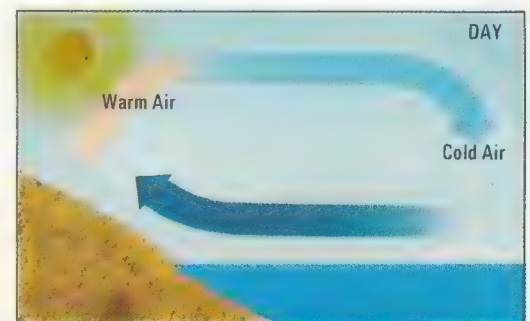
and cloth are poor conductors. The handles of pans and kitchen utensils are made of plastics or wood because these materials will hardly even become warm at the temperatures used for cooking. We encase ourselves in clothes to stop body heat from leaving our bodies (though some gets through, otherwise we would boil), and we insulate water heaters and roofs in houses to cut down heat losses and save fuel costs. Extra layers of fat beneath the skin similarly provide insulation in polar animals such as whales and seals.

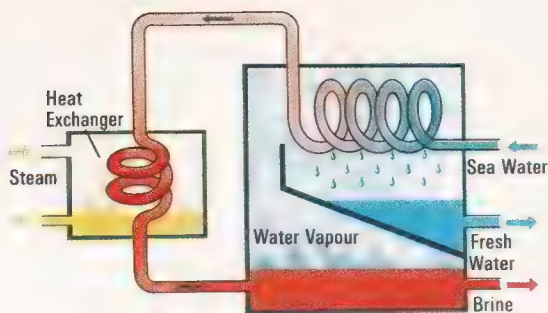
Liquids also are poor conductors (apart from mercury, which is a metal). So too are gases. The fur and feathers of animals trap layers of air next to the skin so that heat does not escape. This is why ducks can swim happily in freezing water. We ourselves are similarly insulated because our clothes, parti-

THE WORLD'S WINDS

Set patterns of winds occur throughout the world. The trade winds blow towards the equator, but at the equator it is calm. At temperate latitudes, the prevailing winds come from the west, and winds also blow away from the poles. These general movements of the atmosphere are convection currents produced by the Sun's heat reaching the Earth. This is greatest at the equator, and causes air to rise as it is warmed. Colder air moves in to replace it, producing the trade winds. The rising air spreads out on each side of the equator, becoming colder and eventually descending again and returning to the equator. Similar convection currents produce the westerlies and the polar winds. The Earth rotates beneath them as they move, causing them to veer in direction.

Convection also produces on-shore gusts at the seaside by day and off-shore breezes by night. During the day the land absorbs the Sun's heat more readily than the sea. Air therefore rises above the land, and cooler air blows in from the sea to replace it. At night the land cools more quickly than the sea. Air therefore rises above the sea and winds flow from the land towards the sea. (See below).





Left: A heat exchanger is used to transfer heat from a source of heat to a place where it is needed. The source of heat is a hot liquid or gas, such as steam, and it circulates in a chamber through which runs a pipe containing another liquid or gas that needs to be heated. Here, a heat exchanger is used to transfer heat from hot steam produced by a nuclear reactor to a plant for distilling fresh water from sea water. The cold sea water is heated in the heat exchanger, producing water vapour that condenses on the cold inlet pipe to give fresh water.

cularly woollen garments, trap air. Double glazing keeps the heat in because the layer of air between the two panes of glass prevents conduction through the window. However, heat transfer in liquids and gases is complicated by movement of the liquid or gas.

Convection

If you place your hand over a radiator, you will feel a lot of heat rising from it, even though not much heat is to be felt in front of it. The hot, rising air eventually spreads throughout the room, bringing warmth to every corner. This kind of heat transfer is known as convection. The radiator—or any other heater placed in a room—warms the air next to it. The air expands as it gets hotter and becomes less dense than the surrounding air. It therefore rises from the heater and colder air comes in to replace it. This too is heated and rises, and a current of warm air is circulated throughout the room. This air movement is known as a convection current. Convection also occurs in liquids. As a kettle is heated, convection currents in the water automatically stir it so that heating occurs evenly throughout the water. When it boils, all the water is at boiling point.

Radiation

If you stand in front of an open fire, you will feel the warmth soaking into you. Conduction cannot be transferring the heat, because there is air between you and the fire and air is a poor conductor of heat. But convection cannot occur either, because the air heated by the fire is escaping up the chimney. The heat is reaching you by radiation; heat rays produced by the fire move through the air and warm everything that absorbs them. All objects produce heat rays, the amount depending on their temperature.

Heat rays are also known as infra-red rays and they are part of the electromagnetic spectrum (see page 86). They cause heating because they vibrate at about the same rate as atoms and molecules vibrate. Atoms and molecules therefore take up the energy of the rays by increasing their intensity of vibration—that is, getting hotter.

The Sun heats the Earth by radiation because heat rays travel through space. They may also travel through things that are transparent—glass and air, for example. But heat rays exist at various wavelengths depending on the temperature of their source, and glass is transparent to heat rays from the Sun but

not to heat rays from cooler bodies. The Sun's heat therefore passes through glass and warms objects behind it. However, the heat rays then produced by the warm objects do not pass back through the glass. This is how a greenhouse stores heat. A similar effect warms the Earth. The atmosphere acts like the glass in the greenhouse, and prevents the heat received by the surface of the Earth from immediately leaking away into space by radiation.

Because transparent objects tend to allow heat rays to pass through them, it may seem that an opaque object would block them and act as insulation. But this is not completely true. A dark object will absorb the heat rays, just as it absorbs light, and it will become warmer. As its temperature increases, it will radiate the extra heat away again. But a white or silvered object will reflect heat rays, just as it reflects light, and it will not get warmer. This has been known for a long time by people in hot countries, who wear white clothes. Electric fires have shiny reflectors to help radiate their heat outwards; you will find very little heat produced behind an electric fire.

Below: A fire fighter wears a special suit so that he can walk through an inferno and remain unharmed. The silvery surface of the suit reflects away heat, and it is woven from fibres of asbestos which is a very poor conductor of heat.



The Effects of Heat

Heat has several effects, some very obvious and some virtually invisible. Burning is a particularly striking effect and so too is cooking; one may of course lead to the other if insufficient care is taken. Both burning and cooking happen because chemical reactions generally double their speed with an increase of 10°C in temperature. Cooking is a chemical reaction between the substances in the food. Raise the temperature of the cooker and the reaction takes place more quickly and the meal is ready earlier. Raise it too much and the ingredients begin to react quickly with the air and they char and burn. Chemical processes in industry are carried out at high temperatures so that they take place quickly and economically. These processes take up heat as they proceed, but some give out heat. Adding quicklime or sulphuric acid to water produces heat, and so too does the chemical reaction of an explosion and, once it gets going, a fire.

One other property of heat is also very obvious: the fact that solids melt and liquids boil when heated. The heat involved in changes of state is dealt with on pages 154 and 155.

Expansion and Contraction

One effect that heat has on all substances is expansion. The increased vibration of the molecules forces them apart slightly and, in



Above: An iceberg floats because water expands on freezing, making it less dense than cold water.

Below: Rivets are applied hot, so that they contract on cooling and produce a strong, tight join.



solids and liquids, size increases. Imagine the molecules being people on a dance floor and the heat being the speed of the music; as the music gets faster, the people dance more wildly and move apart to get out of each other's way. In real life, the increase in size due to expansion is imperceptible; a bar of steel, for example, gets longer by only a hundred-thousandth of its length for every degree Celsius rise in temperature. Before any expansion became noticeable to the eye, the bar would have melted. Brick and stone expand even less, and silica and a nickel alloy called invar hardly expand at all. Water increases its volume, except near freezing point, by one five-thousandth for every degree Celsius rise in temperature. All substances contract in size by the same amounts when they lose heat as they expand when heated.

However imperceptible expansion and contraction may be, their effects are of great use to us. Expansion and contraction are very powerful and no force can prevent them taking place. Girders are riveted together by fixing them with a red-hot rivet; as the rivet cools, it contracts and forces the girders together in a strong and tight hold. Allowance must be made for expansion and contraction in bridge building. A bridge may be so long that expansion becomes significant in the summer heat, and the structure could buckle if it were not free to move. Bridges are therefore placed on rollers at the ends, or they are

built in sections that interlock as the fingers of two hands interlock. Electric cables and telegraph wires must be allowed to sag a little when they are hung from pylons or poles, otherwise they would snap when contraction takes place in winter.

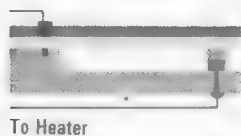
Thermostats make use of expansion and contraction to control heating systems and cookers. The thermostat acts to switch the heating on when the temperature falls too low and to switch it off again when the required temperature is reached. It simply contains an element designed to expand and switch off the supply of heat when it gets too hot and to contract and switch it on again when it gets too cold. Many thermostats contain a bimetallic strip made of two different metals, usually brass and iron, that expand by different amounts. A bimetallic strip therefore bends as the temperature changes, and it can be designed to operate a switch in a thermostat. A simple thermometer can also be constructed with a bimetallic strip (see page 150).

The expansion and contraction of liquids is made use of in the mercury or alcohol thermometer. The bore is so narrow in the thermometer that the expansion and contraction of the liquid inside is readily seen. In most liquids, contraction occurs as the temperature drops, and when the liquid freezes to a solid, the solid is more dense than the liquid and sinks to the bottom. Water, however, does not behave in this way. Below

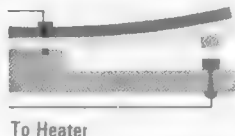
4°C, it begins to expand as the temperature falls and, as it freezes, more expansion occurs. As a result, ice is less dense than cold water and floats in water. If it did not, ice would sink as it formed and whole lakes and rivers might freeze solid in winter. Because ice floats, a layer of ice forms over the water and prevents further freezing beneath. Fish can live below the ice and survive the winter.

Gases expand and contract by much greater amounts than solids or liquids. The increase or decrease in temperature speeds or slows the molecules, and produces a change in pressure if the volume does not change, or a change in volume if the pressure remains unaltered. These effects are the basis of two of the gas laws (see page 54). Charles' law relates temperature to volume, and it happens that the volume of any gas increases by $1/273$ of its volume at 0°C for every degree Celsius rise in temperature.

The principal result of expansion and contraction of gases is the production of convection currents (see pages 150, 151). An expanded gas has a lower density than a cooler gas, and hot gases therefore always rise above cool gases. A hot-air balloon makes use of this effect, gaining lift as the hot air inside the balloon endeavours to float above the cooler air surrounding it. Glider pilots seek thermals, currents of air that rise from warm parts of the ground, such as roads or roofs (which absorb more heat than their surroundings), to gain height.



To Heater

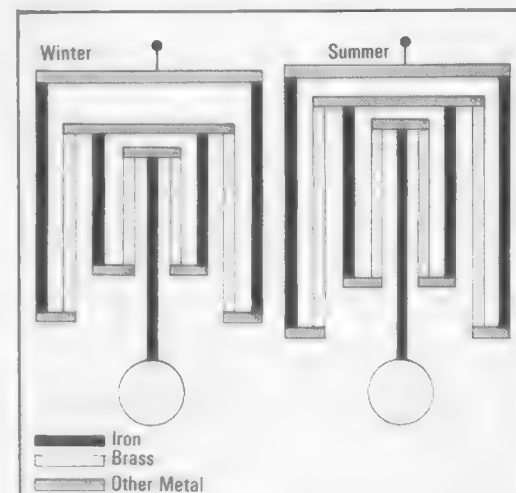


To Heater

Left: A thermostat contains a bimetallic strip of iron (above) and brass (below). When cool, the strip is straight; the contact is closed (left) and current flows through it to a heater. As the temperature rises, the brass expands more than the iron, making the strip bend. At one stage contact is broken and the current stops flowing (right), cutting off the heater. When the bimetallic strip cools down, contact is made again and the current flows once more.

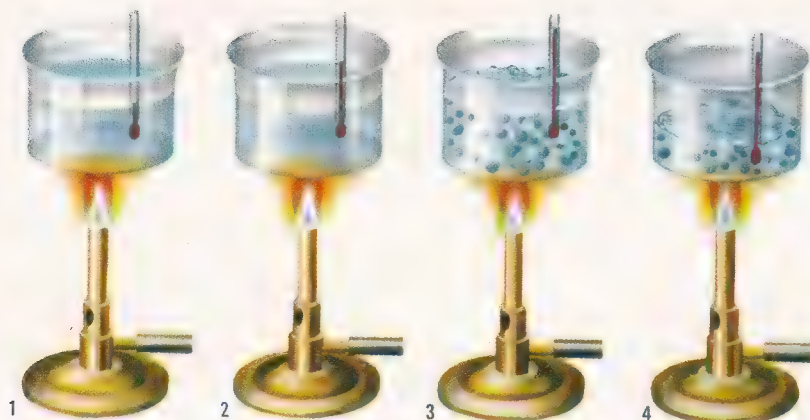


Tight-fitting bearings are inserted into a linkage by first cooling them in liquid nitrogen to make them contract. They are then slipped into place, and as they warm up, they expand and grip the linkage firmly.



THE COMPENSATED PENDULUM

Many clocks keep time with a pendulum, the length of the pendulum regulating the clock. If the pendulum expands in summer, it will take longer to swing and the clock will run slow. The compensated pendulum remains the same length whatever the temperature because of an ingenious arrangement of rods of brass and iron, which expand by different amounts. As the temperature increases, the expansion of the iron rods lowers the bob of the pendulum while the expansion of the brass rods raises it. Brass expands half as much again as iron and the rods are arranged so that the downward movement equals the upward movement and the pendulum overall remains the same length. In this way, it keeps perfect time throughout the year.



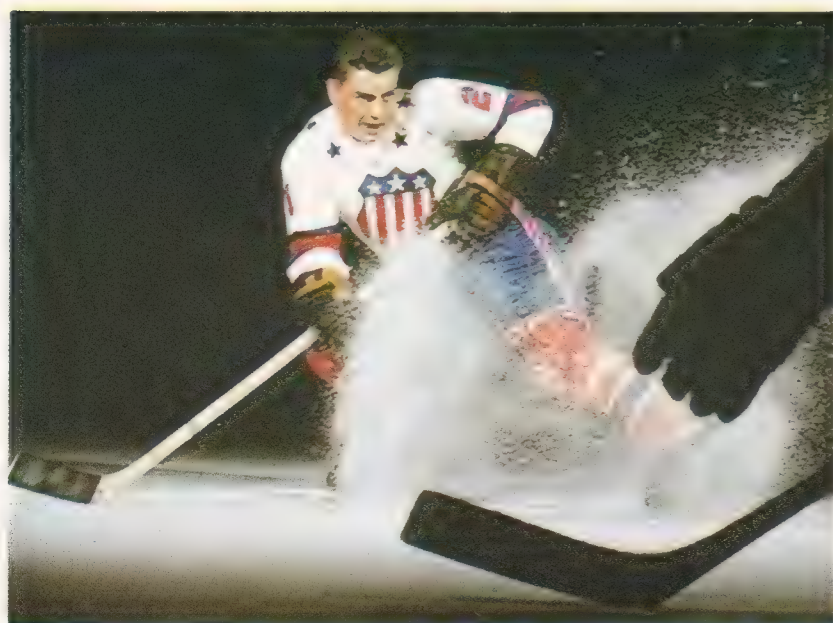
Hidden Heat

An easy way of finding the direction of the wind is not to look for a weather vane but to wet your finger and hold it in the air. As the wind strikes it, your finger suddenly feels cold on the side from which the wind is blowing and it dries more quickly on that side. The wind is somehow taking heat away from your finger, but the method works even when it is very warm so the reason is not that the wind is blowing cold air on your finger. The water on your finger is evaporating quickly because the wind is continually blowing away the water vapour that is produced by the liquid water on your finger. Every liquid produces vapour, and the change from liquid to vapour or gas requires heat. This heat can only come from the water; it therefore loses heat and lowers its temperature.

The heat involved in changes of state is called *latent heat* (meaning hidden heat), because it seems to come from or go to nowhere. Evaporation is an unusual change of state in that it can take place over a wide range of temperature. Other changes of state

Above: As a beaker of water is heated, it takes up heat and its temperature rises (1 and 2). When it reaches boiling point, it begins to boil (3). More heat is needed to keep it boiling, but the temperature does not increase (4). A lot of heat is needed just to change water to steam. This heat is called latent heat.

Below: Ice melts if it is compressed, because melting points vary with pressure. Two blocks of ice can be made to stick together simply by pressing them. Water forms where they meet, because the pressure lowers the melting point of ice, and then refreezes as the pressure is released. Ice skaters momentarily cause the ice to melt beneath their skates, enabling them to skim over the ice.



—freezing, melting and boiling—take place at fixed temperatures. As a change of state occurs that requires heat—melting or boiling—latent heat is taken up by the solid or liquid to make the change. The temperature of the substance being heated remains constant while the change takes place. Latent heat must be removed from a liquid to produce freezing; the temperature drops until freezing begins and then remains steady as it takes place. This explains why it takes such a long time to make ice in a refrigerator. While the water cools quickly, it freezes only slowly because it gives out latent heat as it does so. The refrigerator takes away this extra heat as fast as it can.

The production or absorption of latent heat produces a fixed melting or freezing point and a fixed boiling point for every substance. For solid-liquid change, the energy change is called the latent heat of fusion and for liquid-vapour change, it is called the latent heat of vaporization. The amount of latent heat involved in a change of state is surprisingly large. It takes nearly as much heat to melt a piece of ice as it does to raise the same mass of water from freezing point to boiling point. And it then requires over five times as much heat to change the boiling water to steam.

Condensation—the change from vapour to liquid—is like evaporation in reverse. It occurs when the air is saturated with water vapour and can hold no more. The air's capacity for holding water vapour decreases as the temperature drops and there comes a point at which water vapour leaves the air and condenses as liquid water. Dew occurs as water vapour in the air condenses on the ground. Clouds and fog occur when water vapour condenses as droplets in the air. As they do so latent heat is given out. The formation of fog may prevent a frost occurring, because latent heat is given out as it forms. If the air remains clear on a winter night, a frost is more likely to occur. Steam heating depends on the latent heat given out as steam condenses inside the pipes or radiators.

Latent heat can easily be explained by considering the action of the molecules. When a solid melts to a liquid and a liquid boils to form a gas or evaporates to a vapour, the molecules suddenly get much farther apart as the change of state takes place. Energy is required to overcome the attraction between the molecules. Similarly, energy is given out as the molecules settle into closer patterns on condensation and freezing. This energy is the latent heat.

Pressure and Heat

Pressure affects the change of state of all substances. As a liquid is heated it gives off more and more vapour. When a liquid boils, it does so because the pressure of its vapour has risen to the same value as the pressure of the air above it. At lower temperatures, its vapour pressure is not sufficient to equal



the pressure of the air and it does not boil. However, if the air pressure is lowered, the liquid will boil at a lower temperature. This happens at high altitudes; water boils at much lower temperatures on high mountains. Similarly, an increase of pressure will raise the boiling point. This happens in a pressure cooker. A little water boils at the base of the cooker, producing steam. The cooker is closed, so that as more water boils the steam pressure builds up inside. This raises the boiling point of the water and therefore the temperature of the steam. The food inside is steamed at a temperature above normal steaming temperature (100°C) and cooks more quickly.

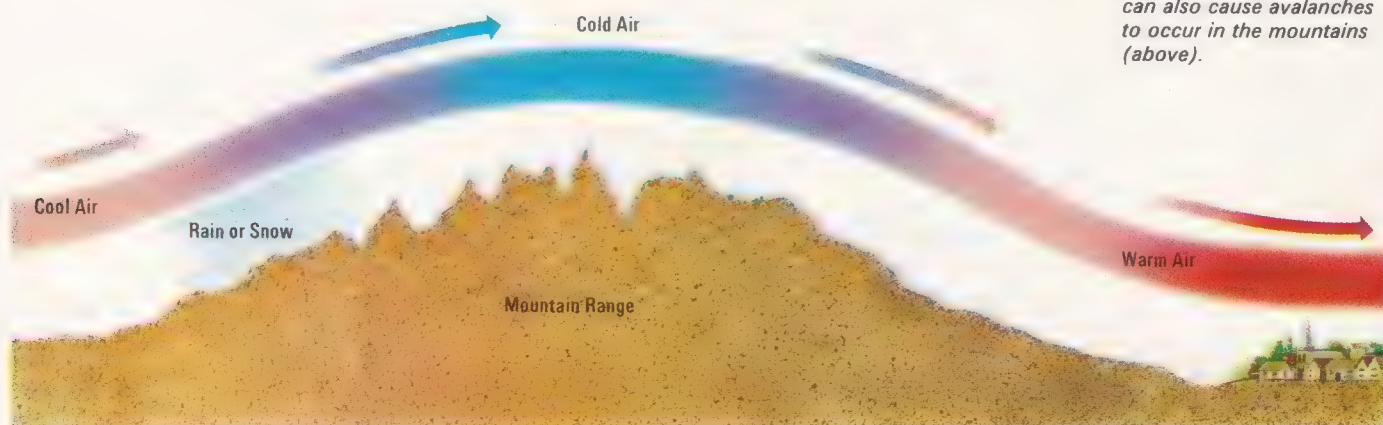
Pressure may also lower melting points. If ice is compressed sufficiently, it will melt. A hard snowball can be made by compressing snow in the hands; the ice crystals in the snow melt slightly and then instantly refreeze as the

pressure is lifted and bind the snow into a hard ball.

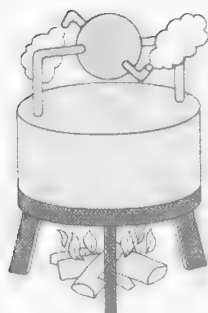
If the pressure of a gas is lowered, its molecules move farther away from each other as it expands. This movement takes up energy and unless heat is supplied to the gas, its temperature will fall. Similarly, if pressure is increased and heat is not allowed to escape from the gas, its temperature will rise. This kind of heat production or loss is called an *adiabatic* process. It can easily be demonstrated with a bicycle pump. If the handle is forced in rapidly and a finger placed over the nozzle to prevent the air escaping, the pump will get hot.

Adiabatic heat changes explain why the air is cooler at high altitudes. As air rises, it expands and its pressure decreases; no heat can get to the air (the Sun's heat passes straight through it) and so its temperature falls.

The snow covering plains lying in the lee of mountains often melts unexpectedly as warm winds descend from the snowy heights of the mountains. These winds are known as föhn winds in Europe and chinook winds in America. As the wind meets a mountain range, it ascends and the air becomes cooler. It sheds any moisture it has as rain or snow on the mountain slopes and gains some latent heat. But as the air rises further, it expands adiabatically and cools. The dry, cold air then blows over the snowy summits of the range and descends rapidly to the plains on the other side. As it does so, it is compressed and becomes much warmer. Föhn winds aid agriculture by melting winter snows. But they can also cause avalanches to occur in the mountains (above).



Putting Heat to Work

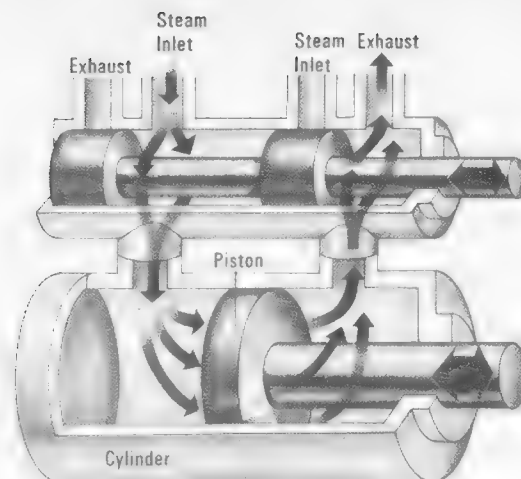


Above: The ancient Greek engineer Hero, who lived during the first century AD, invented a famous steam engine that bears his name. In Hero's engine, steam from a boiling kettle is fed through pipes to a hollow sphere with two vents on opposite sides. The sphere is mounted so that it can rotate. Steam rushes from each vent, pushing the sphere in the opposite direction and making it spin. The lawn sprinkler works on the same principle, but uses a jet of water instead of steam. Slave labour was plentiful in Hero's time, and his engine was never used to provide power.

Until about 1800, people believed that heat was a kind of fluid called *caloric*. All substances contained this fluid. When a substance was hot, caloric was escaping from it. The caloric theory was disproved by an American scientist known as Count Rumford (a title that he gained in Europe; his original name was Benjamin Thompson and he lived from 1753 to 1814). In 1798, Rumford noticed in a munitions factory that cannons became very hot as they were bored. The caloric theory held that heat fluid would escape from the cannon as pieces of metal were cut from it; but Rumford reckoned that if this was so, the metal would have to contain so much heat that it would melt. He then demonstrated that using a blunt borer did not result in any cutting away of pieces but produced even more heat than before. He reasoned that the motion of the borer was being converted into heat. From this, it followed that work could be converted into heat and Rumford found approximately how much work is equivalent to how much heat. An accurate figure for this mechanical equivalent of heat was later established by Joule (see page 68).

If work produces heat, then heat should be able to produce work. In fact, this was already being done in Rumford's time in the steam engine. Later many more engines that use heat as a source of energy were invented. They include the petrol engine, steam turbine, jet engine and rocket engine.

There are two basic kinds of heat engines: external combustion engines and internal combustion engines. In external combustion engines, heat is produced outside the engine and taken to the chamber where work is produced. For example, steam is raised in a



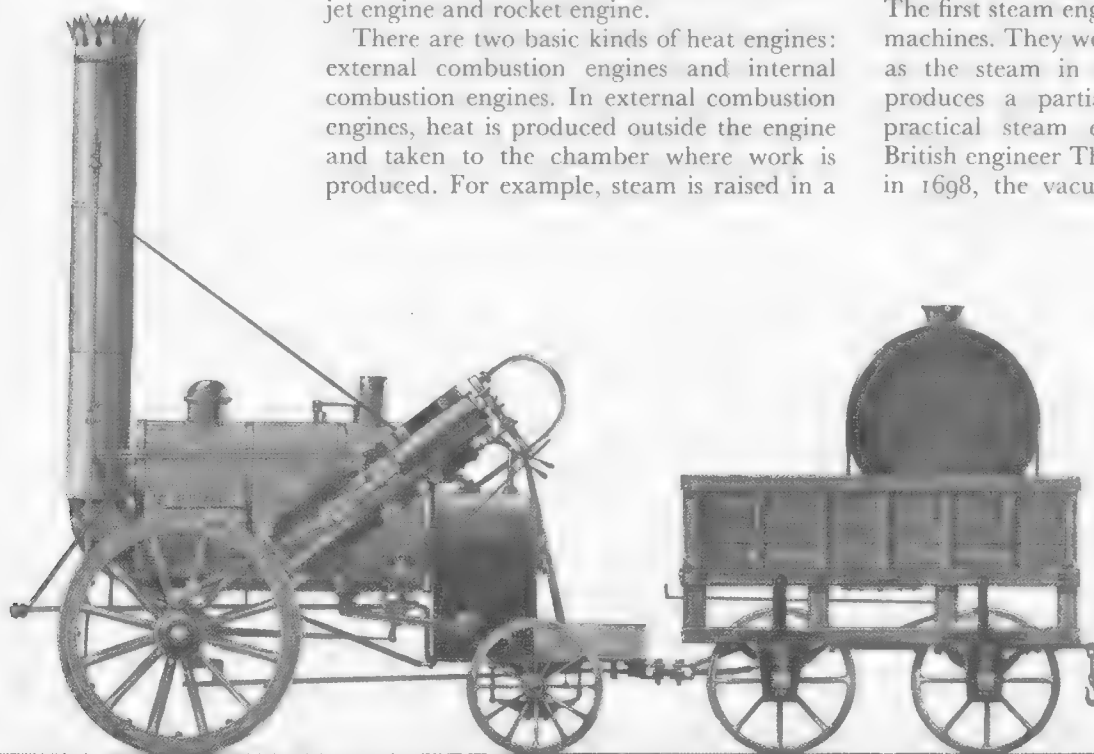
In the reciprocating steam engine, a piston is forced up and down a cylinder by steam pressure. Ports open and close alternately to admit high-pressure steam to one side of the piston while opening an exhaust on the other side. Steam locomotives are powered by reciprocating engines.

boiler and then conducted to a steam engine. In internal combustion engines, heat is produced inside the working chamber, generally called the combustion chamber. Petrol and jet engines are internal combustion engines, as is the rocket.

The power of all heat engines depends on the temperature at which heat is put to use in the engine, and the temperature at which it leaves the engine. In between, some heat will have been converted into work and so the greater the temperature difference (in kelvins), the greater the work done. In a petrol engine, this temperature difference is that between the temperature of the burning fuel and the temperature at the exhaust and at the surface of the engine. No engine uses up all its heat. In the petrol engine, only about a third is used; two-thirds has to be rejected into the atmosphere.

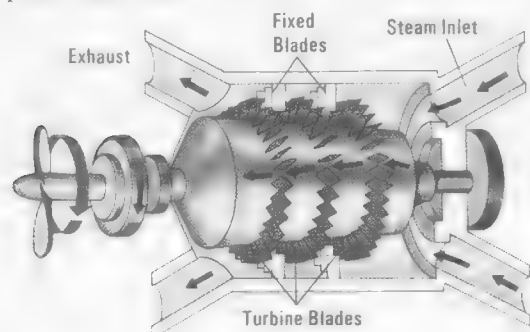
The Steam Engine

The first steam engines were slow, ponderous machines. They worked on the principle that as the steam in a chamber condenses, it produces a partial vacuum. In the first practical steam engine, invented by the British engineer Thomas Savery (1650–1715) in 1698, the vacuum was used to suck up



The Rocket, built by the British engineer George Stephenson in 1829, was the most famous of the early steam locomotives. Steam raised in the boiler drove a piston back and forth in the cylinder, and the connecting rod turned the wheel. The few steam locomotives that still exist work in the same basic way.

water from mines; it had no moving parts other than valves. Thomas Newcomen (1663–1729), another British engineer, utilized the same principle to drive a piston up and down a cylinder and produce mechanical energy. Like all heat engines, these early steam engines worked by a cycle of operations repeated over and over again to obtain continuous power. However, the cycle was impossibly slow, because the chamber containing the steam had to be cooled every time to produce condensation of the steam inside and then heated to admit the steam without it condensing. James Watt (1736–1819), another British engineer, shortened the cycle time in 1769 by connecting a condenser to the steam chamber. Steam was admitted to both the chamber and condenser, but the condenser was kept cold and the chamber hot. As the steam condensed in the condenser, it produced a partial vacuum in the condenser and the steam chamber; there was no need to cool and heat the engine alternately and it would drive the piston up and down as fast as its power allowed.



In a steam turbine, high-pressure steam is directed through groups of fixed blades to strike the blades of a series of turbine wheels. The steam expands as it passes through each set of turbine blades, driving the wheels round. The fixed blades direct the steam onto the turbine blades at the correct angle. Ships and electric generators are powered by steam turbines.

Even this engine was not very powerful; its motive power still came from the pressure of the air pushing the piston into the vacuum inside the steam chamber. Watt realized that steam could be generated at high pressure in a powerful boiler, and that it would give more power than air pressure. He is reputed to have thought of this as a boy while watching the lid of a boiling kettle jog up and down, though this story may later have been invented to explain his subsequent career. In fact, the motive power of steam had been demonstrated long before by the French physicist Denis Papin (1647–1712). At about the same time as Thomas Savery developed his steam engine, Papin constructed a model engine in which high-pressure steam made by heating water inside a cylinder forced a piston up the cylinder. The piston returned when the cylinder was cooled and the air pressure on the other side pushed it back.

Papin's engine was not practical, but Watt developed an engine in which high-pressure steam was admitted alternately to both sides

of a piston and drove it to and fro. The higher the temperature of the steam, the greater its pressure and the more power it has to force the piston back against air pressure on the other side. As in all heat engines, the power produced depended on the temperature difference over the engine. Watt's steam engine drove the first railway engines. It lives on in the few steam locomotives still in use today.

Modern steam engines do not use pistons and cylinders, but contain rotating sets of turbine blades. The high-pressure steam spins the blades of the turbine just as a wind rotates a windmill. As the steam passes through the blades, it expands and loses pressure and heat. The steam turbine was developed by the British engineer Sir Charles Parsons (1854–1931) in 1884. It was much more useful than a piston engine, in which the power is produced as a reciprocating (up-and-down) motion, because the rotary power can go directly to the propellers of a ship or the shafts of electric generators in power stations, the two principal uses of the steam turbine.

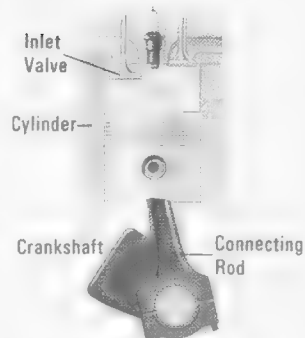
The Petrol Engine

In the petrol engine and other internal combustion engines, ignition of the fuel inside the combustion chamber causes the air and gases produced by burning of the fuel to expand violently. The force of this expansion is then turned into useful power. In the petrol engine, it usually drives a piston up and down a cylinder and a crankshaft driven by a connecting rod beneath the piston converts this motion into rotary motion. Drive shafts take the rotary motion to the wheels through the clutch and gears. Most petrol engines contain more than one cylinder to give more power.

A petrol engine is a complex machine. The pistons move up and down the cylinders several thousand times a minute and with each movement fuel has to be admitted, ignited at a precise instant, and the exhaust gases removed before more fuel is introduced. The simplest petrol engine works by a two-stroke cycle; that is, all these operations take place within one upstroke of the piston and one downstroke. As the piston moves up, the fuel—a mixture of petrol vapour and air—is admitted to the lower portion of the cylinder and the crank-case containing the crankshaft, while fuel in the part of the cylinder above the piston is being compressed. At the top of the upstroke, a powerful surge of electric current produces a spark in the sparking plug and the fuel ignites, forcing the piston down. Towards the bottom of the downstroke, the exhaust gases leave and then fuel is admitted from the crank-case. The fuel inlets and exhaust outlets are side ports opened and sealed by the movement of the piston.

The two-stroke engine is comparatively simple and cheap, but it does not develop great power and its rapid action uses up fuel quickly. It is used in motorcycles, but motorcars contain a four-stroke engine for power and economy. In this engine, fuel and exhaust

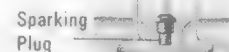
THE FOUR-STROKE CYCLE



On the first stroke, or induction stroke, fuel is admitted through the inlet valve at the top of the cylinder as the piston moves down.



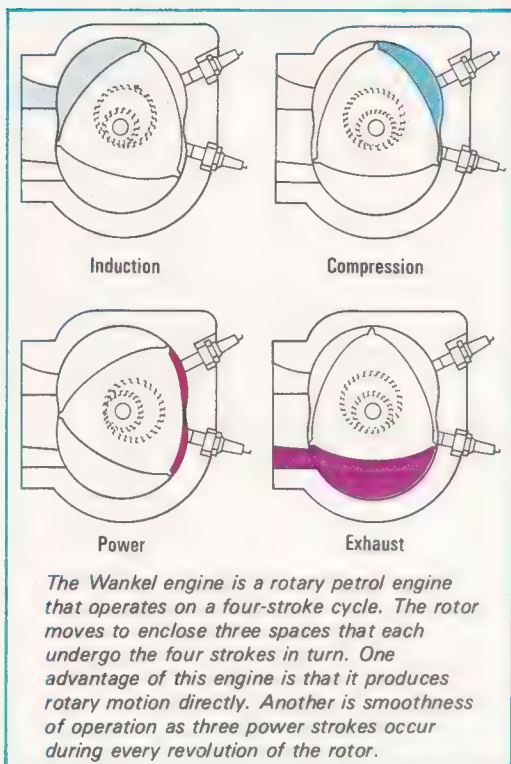
On the second stroke, or compression stroke, the inlet valve closes, and the piston moves upwards, compressing the fuel vapour.



On the third stroke, or power stroke, the sparking plug fires and the fuel ignites, forcing the piston down the cylinder.



On the fourth stroke, or exhaust stroke, the exhaust valve opens and the piston moves up the cylinder, expelling the exhaust gases.



gases enter and leave the combustion chamber through valves. On the first downstroke of the piston or induction stroke, fuel enters the cylinder. On the first upstroke or compression stroke, it is compressed. Ignition then occurs and expansion of the gases in the cylinder occurs on the second downstroke, the power stroke, and on the second upstroke, the exhaust stroke, the exhaust gases leave. The cycle then begins again. As power is produced only during the power stroke, a flywheel is connected to the crankshaft to keep the pistons moving during the other strokes.

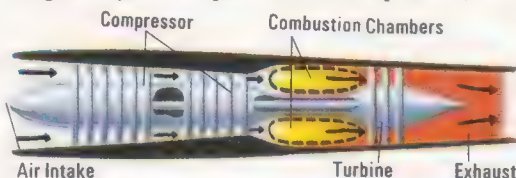
The first practical internal combustion engine was a four-stroke engine invented by the German engineer Nikolaus Otto (1832–91) in 1876. It ran on coal gas. A light but powerful engine using petrol as a fuel was soon developed and it was this engine that made possible both the motorcar and the aircraft. In between these two innovations came a development of the petrol engine that was of use for neither but far-reaching all the same. In 1897, the German inventor Rudolf Diesel (1858–1913) perfected the engine that bears his name. The diesel engine requires no ignition system. Instead the air in the cylinder is compressed strongly in an upstroke of the piston and gains heat adiabatically (see pages 154–5). At the top of the stroke, fuel is sprayed into the cylinder and immediately ignites. A light, cheaper oil like paraffin can be used instead of petrol, but the diesel engine is not very suitable for cars as it is heavy and somewhat sluggish. But it performs admirably for heavy transport, and for driving electric generators. Many modern railway locomotives are driven by diesel-electric engines, which are electric motors driven by electric generators powered by onboard diesel engines. Electric traction is

very suitable for railways, and the use of diesel-electric locomotives saves the cost of installing electric wiring along the track.

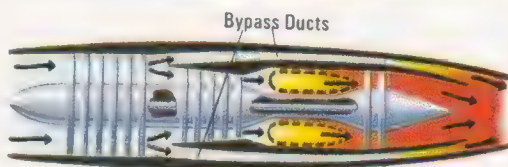
As rotary steam power has superseded the reciprocating steam engine, engineers have looked for ways of producing rotary power in the internal combustion engine. A recent development in this direction by the German engineer Felix Wankel (1902–) has resulted in the Wankel engine, which is now fitted to several cars. In this engine, the piston is replaced by a rotor shaped like a rounded triangle that rotates in an elliptical chamber. As it does so, three spaces left between the rotor and chamber each in turn undergo the four-stroke cycle.

The Jet Engine

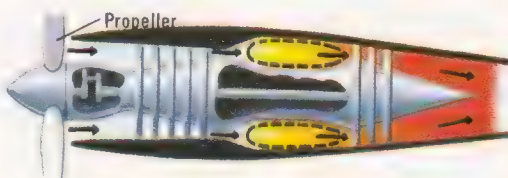
However, a rotary internal combustion engine of very high power also exists in the gas turbine. This engine was developed by the British engineer Sir Frank Whittle (1907–) in World War II. Its high power makes it most suitable for aircraft, in which it is better known as the jet engine. Air is drawn into the engine by a compressor, is compressed, and



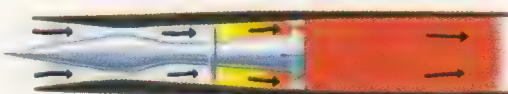
In a turbojet engine, a compressor draws air into the engine and compresses it. Fuel is sprayed into the combustion chambers and burns in the air. The gases produced expand rapidly, driving a turbine that is connected to the compressor. The jet of gases that leaves the engine acts to thrust it forwards.



In a bypass turbofan engine, the compressor has fan-like blades to draw in more air, some of which is diverted around the combustion chambers to the exhaust. This action produces less noise and more thrust, making the engine useful for airliners.



In a turboprop engine the turbine also drives a propeller as well as the compressor. Some thrust is also developed to power the aircraft.



The ramjet is the simplest form of jet engine. It has no compressor, and the air is 'rammed' into the engine by the forward motion of the engine. The ramjet can therefore come into action only when it is already moving.

Above: A Sprint missile undergoes a firing test. The missile is powered by a two-stage solid propellant engine, and guided by radar. It is intended to intercept enemy aircraft.

Right: The Lockheed SR-71A, the world's fastest jet aircraft. It can reach a speed of more than 3,500 kilometres an hour. The aircraft is used for reconnaissance at very high altitudes.

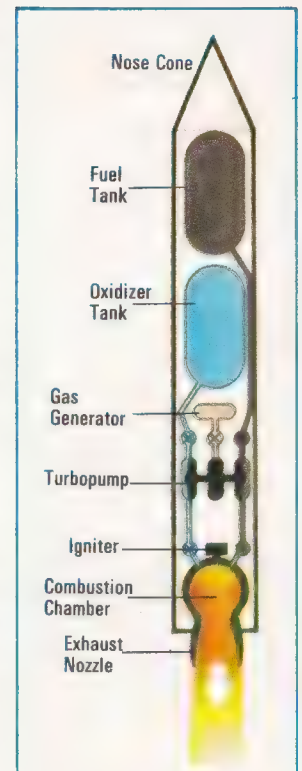


enters combustion chambers where it mixes with the fuel. Expansion occurs as the fuel burns and the hot expanding gases power a turbine before leaving the engine by the exhaust pipe. The turbine is connected to the compressor and drives it. In most engines, motive power is produced as a reaction to the motion of the exhaust gases; the expansion of these gases in the engine thrusts it forward as they move backward and out of the exhaust. The rotary power produced serves only to drive the compressor blades. However, in turboprop engines, the rotary power also goes to propellers to drive the aircraft, and comparatively little thrust is developed.

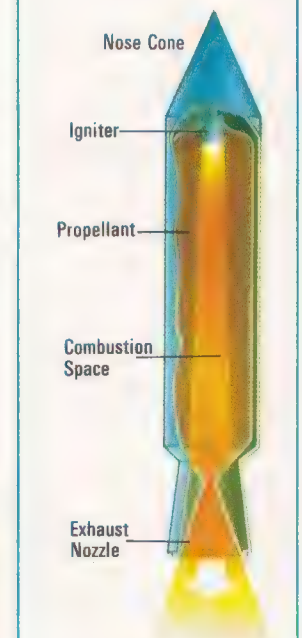
The ramjet is an even simpler form of engine, consisting of an open tube with a fuel supply. When it is moving, air rushes into the tube, mixes with burning fuel, expands and leaves the exhaust, producing a thrust. The ramjet only begins to work when it is already moving, and so is no use for aircraft. However, it was used in V1 missiles fired by Germany in World War II.

The Rocket Engine

The rocket is as simple as the ramjet. It consists of a combustion chamber where two fuels mix and ignite. The expanding gases produced immediately rush from the exhaust, propelling the rocket in the opposite direction. No air is needed; the rocket can therefore work in space and its main use has been in spaceflight. Any fuels can be used that burn with each other. The most powerful rockets use liquid fuels—kerosene or liquid hydrogen together with liquid oxygen—that are pumped from separate tanks into the combustion chamber. Liquid-fuel rockets can be shut down and refired at any time. Solid-fuel rockets are simpler in design and are used where less control is necessary, as in automatic missiles. The solid fuel is contained in the combustion chamber and burns when ignited.



Above: A liquid-fuel rocket contains tanks of fuel and oxidizer that are pumped to the combustion chamber and ignited.



Above: A solid-fuel rocket contains fuel and oxidizer in solid form. The propellant has a hole through its centre along which the gases produced by combustion flow to the exhaust nozzle.





Colder than Cold

The second law of thermodynamics states that heat will, of its own accord, flow only from a hot object to a cold object. Despite appearances to the contrary, the action of a refrigerator conforms to this law. The basic action is simple. A liquid called a refrigerant moves through a closed pipe. When it reaches the interior of the refrigerator, it evaporates inside the pipe. Evaporation takes up latent heat, and the liquid cools as it evaporates. Heat flows from the refrigerator compartment into the vapour in the pipe. This vapour then moves to a condenser on the outside of the refrigerator and condenses to a liquid. Latent heat is given out and lost to the surrounding air from the surface of the condenser. The liquid then moves back into the refrigerator to evaporate again (see page 149). The interior of the refrigerator is kept cold overall because heat is taken from there to the outside. It is possible to work this method in reverse and take heat from outside to heat a house. This heating system is much more economical than using electrical heating. However, at no point does heat actually flow from a colder to a hotter place, as this is impossible. It flows into the cold vapour and away from the warm condenser.

Much lower temperatures can be reached by other methods. If a gas is alternately compressed and expanded, it will gain and lose heat. If it is allowed to lose the heat gained by compression but not to gain heat

Above: A man shatters a rubber tyre after it has been dipped in liquid air. At such a low temperature — about -200°C — many materials that are normally flexible become brittle.

when it expands, it will lower its temperature adiabatically as it expands. Expansion also produces cooling because the molecules in the gas lose energy in overcoming the attraction between them. By repeating these operations in a closed cycle, the gas will eventually liquefy. Liquid air is made in this way. To reach temperatures close to absolute zero, other methods are employed. Demagnetizing certain substances takes energy from them and lowers their temperature. The lowest temperatures — within millionths of a degree of absolute zero — can be obtained by diluting one liquid helium isotope with another. Dilution acts like evaporation and produces cooling.

Refrigeration slows the spoiling action of bacteria, and it is very important as a method of preserving food. The production of liquid gases is also an important industry as many gases can more easily be transported and used in a liquid state. Space rockets are fuelled with liquid oxygen and hydrogen, and liquid nitrogen is used as a simple method of producing deep refrigeration. But these liquids must be handled carefully. Living tissue becomes hard and brittle if immersed in liquid air; a fruit or flower cooled to such a temperature can be shattered into pieces with little effort.

The science of very low temperatures is known as *cryogenics*, and strange things happen in this colder than cold world. Helium remains liquid even near absolute zero unless it is compressed, but it loses all viscosity and becomes a *superfluid*. It will flow up the walls of a container and over the top. Metals and alloys lose all electrical resistance and become *superconductors*. Superconductivity allows the passage of very high electric currents and can produce very intense magnetic fields.

Right: The power capacity of a cable is tested at very low temperatures. Superconducting cables would carry electricity with virtually no loss of power, but maintaining the supercold temperatures required for superconductivity would prove difficult in practice.



Studying the Elements

The study of chemical elements and their compounds requires more and more complicated equipment. The scientists in this laboratory are concerned with the study of radioactive elements, their properties and uses.



The Periodic Table

Until the early 1800s no one really knew much about the nature of matter. Then Humphry Davy and other scientists began to probe systematically into the nature of chemical substances and discover more and more new chemical elements. They realized that these were basic building blocks of matter, which combined together in simple proportion to form chemical compounds. As the properties of the elements became known it became evident that some elements, such as sodium and potassium, had markedly similar properties and were clearly closely related.

With the determination of more accurate atomic weights in the 1850s by Stanislao Cannizzaro and others, chemists such as John Newlands noticed that a relationship existed between the atomic weight and the chemical properties of an element. In 1865 Newlands put forward his *law of octaves*, in which he arranged the elements in order of increasing atomic weight in groups of seven. He noticed a repetition in properties after an interval of seven elements. (In music the octave comprises seven intervals.) For example, sodium had similar properties to lithium which appeared seven elements before. (The rare gases were then unknown.)

The law of octaves, however, was too simple to provide a suitable basis for classification. And in 1869 Dmitri Mendeleev proposed the *periodic law*: that elements arranged in order of their atomic weights show a periodic change in properties. He drew up a *Periodic Table* in which he arranged the known elements in horizontal sequences, or *periods*, of varying length so that when the periods were arranged one above the other, elements with similar properties fell into vertical columns (*groups*). Lothar Meyer made a similar proposal at much the same time. Mendeleev left gaps in his table where he considered elements were missing and predicted what properties these undiscovered elements should have. He was proved right when the elements (such as scandium, gallium and germanium) were eventually discovered. Mendeleev's Periodic Table was modified and extended as new elements were discovered, including the rare gases in 1894.

Mendeleev's classification by atomic weight was not entirely satisfactory because some elements were clearly out of order. It was not until the nature of the atom became better understood in the 1900s that the reason for the anomalies became apparent. The elements appear in the correct positions if they are arranged in order not of their atomic weight but of their *atomic number*—the number of protons in the nucleus of their atoms.

Explaining the Table

A modern version of the Periodic Table appears on page 164. It gives information about each chemical element, up to the recently discovered element number 106. Essentially an atom has a *nucleus* consisting of positively charged *protons* and neutral *neutrons*. Negatively charged *electrons* circle around the nucleus in a number of orbits, or *shells*. The shells are designated K, L, M, N, O, P, Q in order of increasing distance from the nucleus. Each shell can contain a certain maximum number of electrons, the K shell 2, L-8, M-18, N-32, and so on.

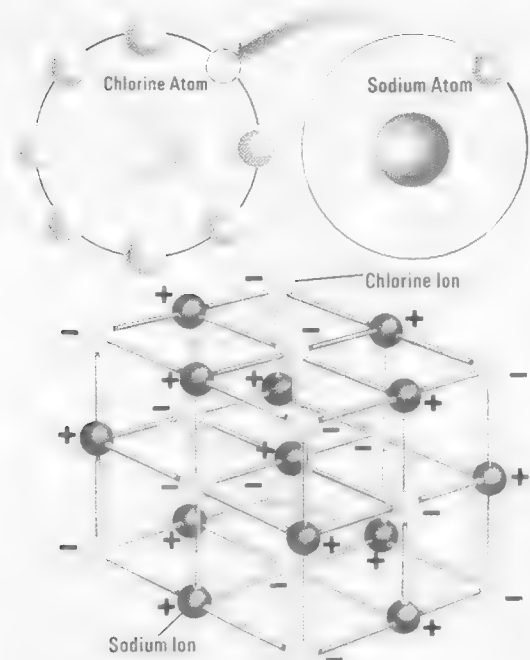
We can relate the position of an element in the Periodic Table to its electronic structure by supposing that the atoms can be built up in a series of steps from the simplest atom. At each step we add a proton, that is, increase the charge on the nucleus by one unit, and add one electron to the planetary system. The single electron of hydrogen (one proton, atomic number 1) circles in the K shell. Addition of another electron to the K shell, which becomes full, gives the helium atom. Hydrogen and helium make up the first, very short period of the Table, Period 1.

When we add another electron, to make lithium, it goes into the next shell, L. We can write the electronic structure of lithium as K², L¹, or simply 2, 1. We can keep adding electrons to the L shell until it becomes full at neon 2, 8. With the next element, sodium, the additional electron goes into the M shell, so that configuration becomes 2, 8, 1. The M shell becomes full (temporarily) at argon (2, 8, 8). The completion of the L and temporary completion of the M shells accounts for the two short periods, 2 and 3, of the Periodic Table.

The addition of an electron to the argon configuration gives the structure of potassium 2, 8, 8, 1. Another electron added gives calcium 2, 8, 8, 2. Then comes an anomaly. The next

The Russian chemist Dmitri Ivanovich Mendeleev, whose work laid the foundation for the modern periodic classification of the chemical elements. Born in 1834 in Tobolsk, Siberia, Mendeleev studied at St Petersburg (now Leningrad) and at Heidelberg, Germany. He wrote a classic chemical textbook Principles of Chemistry between 1868 and 1870. He died at St Petersburg in 1907, by which time the gaps he left in his table had been filled, as he had predicted, by new elements.





Left: A typical example of electrovalent, or ionic, bonding between atoms in which one atom gives the other one or more electrons so that both attain an inert-gas structure — that is, a complete outer electron shell. When they lose or gain electrons, they become positively or negatively charged ions. In electrovalent compounds the ions are held together by electric attraction. In the formation of sodium chloride (common salt) sodium gives an electron to chlorine and becomes positively charged, while chlorine becomes negatively charged. The lower diagram shows the arrangement of the ions in the salt crystal.

ment uranium (atomic number 92), and artificial elements with higher atomic numbers made by nuclear bombardment. The properties of many of these artificial elements are difficult to determine since the elements are intensely radioactive and unstable. Some exist for a fraction of a second only. Lawrencium (atomic no. 103) appears, however, to be the last of 14 actinide elements. The additional elements form part of a main transitional series.

Relationships in the Table

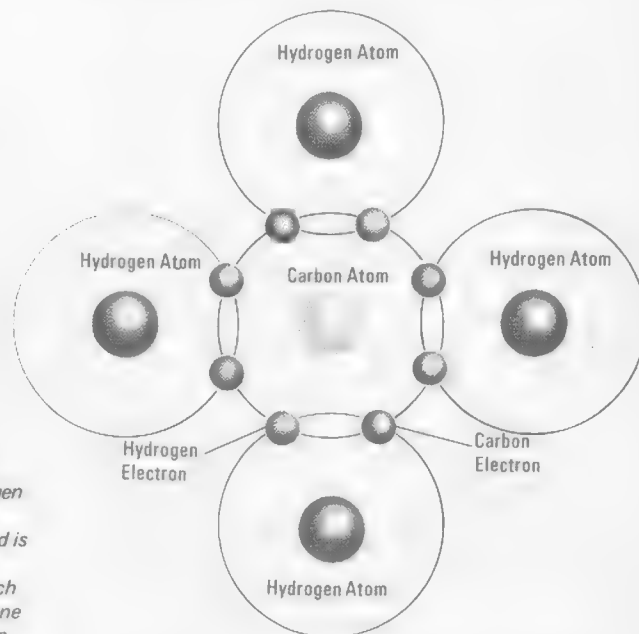
The position of the elements in the Periodic Table can be explained in terms of the progressive build-up of electron shells. With the exception of the transition elements, the elements in the horizontal periods show an additional electron in their outermost shell going from left to right. In the main vertical groups (A) and most of the transition groups (B) the number of electrons in the outermost shell is the same.

electron, instead of going into the outer N shell, goes into the M shell, and for the next element, scandium, we have a structure of 2, 8, (8, 1), 2. The M shell continues to fill up, with just two electrons in the N shell, until nickel 2, 8, (8, 8), 2 is reached. In the next element, copper, the configuration side-steps rather to 2, 8, (8, 10), 1, followed by zinc 2, 8, 18, 2, in which the M shell contains its maximum number of electrons. With gallium, the next element, the build-up of the N shell continues, following on from calcium early in the period, to become full (temporarily) at krypton 2, 8, 18, 8. The 10 elements of the scandium to zinc series, in which build-up of the penultimate shell takes place, are known as *transition elements*. The completion of the M and temporary completion of the N shells account for the first long period in the Table, Period 4.

Similarly, the next long period, 5, is accounted for by temporary completion of the N and O shells between rubidium 2, 8, 18, 8, 1 and xenon 2, 8, 18, 18, 8. Again a transition series begins at yttrium with a switch to the build-up of the penultimate N shell and ends at cadmium 2, 8, 18, 18, 2.

The next long period, 6, has a transition series within a transition series. The 10 elements of the main transition series lanthanum to mercury are marked by the expansion of the penultimate P shell from 8 to 18 electrons. But between lanthanum and the next main transition element, hafnium, there are a further 14 elements, formed by the build-up of the O shell from 18 to 32 electrons. These elements are known as the *lanthanides* or *rare earths*. Period 6 ends at radon with the configuration 2, 8, 18, 32, 18, 8.

Radon is radioactive, as are the succeeding elements in Period 7, which is analogous to Period 6 in having what appears to be a transition series within a series, the elements of which are called the *actinides* after the first member, actinium. The actinides series includes the valuable naturally occurring ele-



Right: By contrast, the method of combination between carbon and hydrogen involves the sharing of two or more electrons, and is termed covalency. To attain a complete shell each hydrogen atom requires one more electron. The carbon atom requires four more electrons. So when carbon combines with hydrogen to form methane, each hydrogen atom shares one of the carbon atom's electrons. And the carbon atom shares an electron with each of the four hydrogen atoms. There is no overall transfer of electrons as there is in electrovalency, so no ions are formed. In another type of covalency, sometimes called dative covalency, only one of the atoms combining supplies the electrons which the other atom shares.

The number of electrons in the outermost shell in most cases determines the chemical properties of the element, because when atoms combine to form molecules, they usually do so by means of these electrons. Since there is a similarity in electronic structure in the groups and a progression in the periods, it is reasonable to suppose that there would be a similarity in chemical properties in the groups and a progression of properties in the periods. And in general such relationships do occur.

Some atoms combine with one another by losing or gaining electrons to become ions. This is called *electrovalent* or *ionic bonding*. Other atoms combine by sharing electrons, this being termed *covalent bonding*. An alternative name for bonding is *valency*, though this term is gradually going out of use.

The Group 1A elements lithium, sodium, potassium, and so on form a closely knit family. They are all soft, weak and light metals that react vigorously with and de-

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KEY

Heavy Metals

Rare Gases

ACTINIDE SERIES (93-103 are man made)

227	232.04	231.04	238.03	237.05	244	243	247	247	251	254	257	257	255	256
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103

compose water, forming a strongly alkaline solution (such as sodium hydroxide, caustic soda, NaOH). The Group 7A elements fluorine, chlorine, and so on form another strikingly similar family. Its members are poisonous gases, fuming liquids or low-melting point solids, which react vigorously with metals and most other elements, to form compounds such as sodium chloride (NaCl). They also combine with hydrogen to form strong acids such as hydrochloric acid (HCl).

Within the groups there is generally a gradation of properties from element to element, as the atom gets larger and larger. The relative density of the Group 1 elements (alkali metals) increases from 0.53 for lithium to 1.9 for caesium. The melting points vary from 180°C for lithium to 28.6°C for caesium. A similar pattern emerges in the Group 7 (halogen) elements. The densities and melting points increase from fluorine to iodine; fluorine and chlorine are gaseous, bromine is liquid (relative density 3.1), and iodine is solid (relative density 4.9).

Group 0 is the family of inert or rare gases, which are characterized by their almost complete inertness. With scarcely any exceptions, they are incapable of entering into chemical combination with other elements. Their electronic configuration is made up of complete or temporarily complete shells. No electrons are available to combine with other atoms.

So stable is the inert-gas structure that the modern theory of chemical combination, or bonding, assumes that, when an atom enters into combination with another atom, it gains or loses electrons to attain an inert-gas structure. It may acquire the structure of the inert gas at the end of the period in which it lies, or of the inert gas at the end of the previous period.

The sodium atom, configuration 2, 8, 1, for example, very readily loses its outermost electron in chemical combination to attain the structure of neon 2, 8 at the end of the previous period. Chlorine 2, 8, 7 equally readily gains an electron in chemical combination and attains the stable structure of argon 2, 8, 8. The readiness of sodium and chlorine to acquire an inert-gas structure accounts for their great chemical reactivity. Sodium is termed a strongly electropositive metal because of its readiness to lose electrons and form ions. The sodium ion has a positive charge because an electron (negative charge) is missing; it is written Na^+ . For similar reasons chlorine is termed a strongly electronegative non-metal. It readily gains an electron and becomes a negative ion, Cl^- .

The next element after sodium, magnesium in Group 2A, enters into chemical combination by losing its outermost electrons. It has a charge of +2 (or is *divalent*). It does not lose its electrons as readily as sodium, though, and it is less chemically reactive. The same goes for all the elements in Group 2A. They too are metals (the alkaline-earth metals) but they



The irradiation mounting of the nuclear reactor Pluto, which is used to produce radio-isotopes. The powerful radiation in the reactor core can convert normally stable isotopes into radioactive ones, which have more than the usual number of particles in the atomic nucleus. Irradiation can also change one element into another, this being termed transmutation.

are not as electropositive as the alkali metals. Their physical properties are also different: they are harder and have a higher melting point than the alkali metals. Likewise the elements in Group 6A of the Table are non-metals that are less electronegative than chlorine, but still (like oxygen and sulphur) quite reactive. The elements in the middle of the periods are neither definitely electropositive nor electronegative. They often display both metallic and non-metallic character. Boron, silicon, germanium, arsenic and antimony are such elements; they are called *metalloids*.

Thus, briefly, across a period the elements show a gradation from metallic to non-metallic character—from being strongly electropositive to being strongly electronegative. Going down the groups containing non-metals, the elements become increasingly more metallic as their atomic number increases.

The closely knit relationship of the transition elements along the periods becomes apparent when you examine their atomic structure. They usually have the same number of electrons in their external shell, and, since it is this which largely determines their chemical activity, they have similar properties. But their chemistry is influenced by the ability of the electrons in the penultimate shell to enter into chemical combination. This helps to explain why the transition elements display variable oxidation states, or valencies. The presence of colour in the compounds that the transitional elements form is also due to the presence of an incomplete penultimate shell.

Chemical Elements

Actinium (Ac, atomic number 89) Rare radioactive metal found in uranium ores, such as pitchblende, resulting from the decay of uranium-235. First of the actinide series of elements.

Aluminium (Al, 13) Strong, lightweight, corrosion-resistant metal of the boron group (Group 3A), second in importance only to iron. Most abundant metal in the Earth's crust comprising 8%, but its only important ore is bauxite, containing the oxide alumina. It has an oxidation number of 3. The oxide, Al_2O_3 , and hydroxide $\text{Al}(\text{OH})_3$, are amphoteric. The hydrated mixed sulphate with potassium—potassium aluminium sulphate, or potash alum, $\text{K}_2\text{SO}_4 \cdot \text{Al}_2(\text{SO}_4)_3 \cdot 24\text{H}_2\text{O}$ —is typical of the series of compounds called alums. (See page 188.)

Americium (Am, 95) Artificial transuranic radioactive element made in 1944 by bombarding plutonium with neutrons; the fourth artificial element to be made.

Antimony (Sb, 51) Hard, brittle element of weak metallic character belonging to the nitrogen family (Group 5A). It is added to some alloys (such as type metal) to harden them. In compounds it may have an oxidation number of 3, as in the poisonous gas stibine SbH_3 , or 5, as in the pentoxide Sb_2O_5 . It also forms oxides with oxidation numbers of 3 and 4; the trioxide Sb_2O_3 is amphoteric; the others are weakly acidic.

Argon (Ar, 18) The most abundant of the inert, or rare, gases (Group 0), making up about 1% of the atmosphere. Obtained by fractional distillation of liquid air, it is used to fill light bulbs and Geiger counters, as an inert atmosphere in arc-welding and as a carrier gas in gas chromatography.

Arsenic (As, 33) A feebly metallic element of the nitrogen family (Group 5A), whose compounds are deadly poisons. It occurs widely in compounds, such as the sulphide realgar, As_2S_3 , and the mixed sulphide with iron, mispickel, FeSAs . In its compounds it commonly has an oxidation number of 3, as in the poison gas arsine, AsH_3 , and the amphoteric arsenic(III) oxide, As_2O_3 . It can also have other oxidation states, as in the arsenic(V) oxide, As_2O_5 , which gives rise to arsenates.

Astatine (At, 85) The rarest naturally occurring element, which has about 20 known isotopes, none of them stable. It is produced during radioactive decay of uranium, thorium and actinium. It is the heaviest member of the halogen series, and its properties resemble those of iodine.

Barium (Ba, 56) A heavy alkaline-earth metal (Group 2A) which occurs in Nature as the sulphate, barytes, or heavy spar, BaSO_4 ; or as the carbonate witherite BaCO_3 . It bursts into flame on contact with air and decomposes water, with the formation of the hydroxide, $\text{Ba}(\text{OH})_2$, and the liberation of hydrogen.

Berkelium (Bk, 97) Artificial radioactive element obtained by bombarding americium with helium ions; the fifth transuranium element.

Beryllium (Be, 4) A lightweight alkaline-earth metal (Group 2A) with a relatively high melting point (1283°C). Strong, hard and elastic, it is used in alloys to confer these

properties on other metals. It is highly transparent to X-rays. Its main source is the mineral beryl, beryllium aluminium silicate.

Bismuth (Bi, 83) A brittle metal with a reddish tinge, belonging to the nitrogen family (Group 5A). It forms low-melting point, fusible alloys with lead and iron. It resembles antimony chemically, and forms three oxides Bi_2O_3 , Bi_2O_4 , and Bi_2O_5 . The trioxide is basic; the pentoxide is weakly acidic. The metal unites readily with sulphur and the halogens. Bismuth salts are used in soothing medicines for digestive disorders. Bismuth is rarely found native; its chief sources are the sulphide bismuthite, or bismuth glance, Bi_2S_3 , and the trioxide bismite, Bi_2O_3 .

Boron (B, 5) A very important semi-metallic element in the same family as aluminium (Group 3A), whose most familiar compound is borax, disodium tetraborate $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$. The borax-bead test used in chemical analysis relies on the property of fused borax to dissolve metallic oxides to form metaborates, some of which are coloured—cobalt metaborate, for example, is blue. Boron can take two forms—a brown amorphous powder and a black, lustrous crystalline material. The latter is an important semiconductor. Boron is used in control rods for atomic reactors since it readily absorbs neutrons. It combines with hydrogen to form boranes such as boroethane, or diborane (B_2H_6), whose constitution cannot readily be explained by normal theories of bonding. Boron reacts with oxygen to form the amphoteric trioxide B_2O_3 ; with halogens to form halides; and with nitrogen to form nitrides, including the hard-as-diamond crystalline compound, borazon, which is used as an abrasive. Boron will also combine with metals such as titanium and tungsten to form heat-resistant borides.

Bromine (Br, 35) A dark red liquid element of the halogen family (Group 7A), whose vapour is pungent and irritates the eyes and respiratory system. Bromine, which has few uses in the uncombined state, is extracted from sea water. It is highly reactive and forms useful bromides with metals and organic substances. Among the most important are light-sensitive silver bromide, which is used in photographic emulsions, and ethylene dibromide which is used, for example, in petrols to remove lead from the cylinders after combustion. (See page 231.)

Cadmium (Cd, 48) A soft metal of the zinc group (Group 2B), which like tin crackles when deformed. It is obtained mainly as a by-product in lead and zinc smelting and refining. Its main use is for plating metals and alloys to protect them from corrosion. It is used in making control rods for nuclear reactors because it readily absorbs neutrons. It is used with nickel in long-lasting nickel-cadmium storage batteries, and in the Weston standard cell. Bright-yellow cadmium sulphide (CdS), which occurs in nature as the mineral greenockite, is an important pigment for inks and paints. Some cadmium compounds are poisonous and have been responsible for serious water pollution in some industrial regions.

Caesium (Cs, 55) A very soft alkali metal (Group 1A), which resembles sodium and potassium and reacts explosively with water. It loses electrons when struck by light and finds ready application in photoelectric devices. Vaporized caesium is used in the atomic clock (see page 205).

Calcium (Ca, 20) A reactive alkaline-earth metal (Group 2A) whose compounds are widespread in Nature, including the carbonate, CaCO_3 (*chalk and limestone*); the hydrated sulphate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (*gypsum*); and the phosphate, $\text{Ca}_3(\text{PO}_4)_2$ (bones and teeth and the mineral *apatite*). Among its many other industrially important compounds are *quicklime*, the oxide, CaO ; *slaked lime*, the hydroxide, $\text{Ca}(\text{OH})_2$; *bleaching powder*, $\text{Ca}(\text{ClO})_2 \cdot \text{Ca}(\text{OH})_2 \cdot \text{CaCl}_2$, a mixture of calcium hypochlorite with basic calcium chloride; and calcium carbide, CaC_2 , from which acetylene gas is made. (See page 207.)

Californium (Cf, 98) Artificial radioactive transuranic element produced by bombarding curium with helium ions. One isotope (Cf-252) is an intense neutron emitter.

Carbon (C, 6) A typical non-metallic element (Group 4A) whose atoms have the ability to link with each other in long and complex chains to form a larger number of compounds than all the other elements put together. Study of these compounds forms the basis of organic chemistry, so called because living organisms are made up of carbon compounds. Carbon occurs in the Earth's crust as soft, flaky graphite and as hard, crystalline diamond, and in compounds with metals and oxygen as carbonates ($-\text{CO}_3$). The atmosphere contains traces of carbon dioxide (CO_2), resulting from animal respiration and from combustion of carbon-containing materials, such as wood and fossil fuels. Partial combustion of carbon yields poisonous carbon monoxide CO , which is a powerful reducing agent. Carbon dioxide forms the weak carbonic acid in water, whose salts are the carbonates. With sulphur, carbon forms the poisonous and flammable disulphide (CS_2), which is a volatile liquid; large amounts of carbon disulphide are used in the manufacture of rayon and Cellophane. With the halogens, carbon forms compounds such as carbon tetrachloride CCl_4 , a non-flammable liquid used for dry cleaning and in some fire extinguishers. With hydrogen, carbon forms the so-called hydrocarbons, such as methane (CH_4) and ethane (C_2H_6), which form the main constituents in natural gas and petroleum. The radioactive isotope carbon-14 is formed in Nature, and provides a means of dating archaeological specimens.

Cerium (Ce, 58) One of the rare-earth metals (transition Group 3B), which is quite plentiful in the Earth's crust, occurring in the minerals cerite and monazite, for example. The cerium alloy, misch metal, is used in making lighter flints. The yellow ceric sulphate, $\text{Ce}(\text{SO}_4)_2$, is a strong oxidizing agent used in volumetric analysis.

Chlorine (Cl, 17) Industrially the most important of the halogens (Group 7A), chlorine is a poisonous yellowish-green gas that irritates the eyes and respiratory system. Chlorine combines with both metals and non-metals. It combines with hydrogen to form hydrogen chloride, which is strongly acidic and gives rise to a wide range of metal salts, such as sodium chloride (NaCl). The gas is prepared by the electrolysis of brine. It and its compounds are excellent bleaching agents. (See page 231.)

Chromium (Cr, 24) A hard, brittle transition metal (Group 6B) which takes a high polish and finds widespread application in chromium plating. It confers strength and corrosion

resistance to alloys with steel. It was called chromium (colour) because of the colour exhibited by many of its compounds, such as yellow lead chromate, PbCrO_4 , or green chrome oxide, Cr_2O_3 . The red of the ruby and the green of the emerald are also due to chromium compounds. The chromates and dichromates are strong oxidizing agents. Potassium dichromate, $\text{K}_2\text{Cr}_2\text{O}_7$, is used in volumetric analysis. The mixed oxide with iron, *chromite*, FeCr_2O_4 , is the chief ore.

Cobalt (Co, 27) A transition metal (Group 8B) used in high-temperature and magnetic alloys, such as *alnico* (with aluminium and nickel). It resembles iron in its chemistry, but physically it is heavier, stronger, and harder than iron. It forms more complex ions than any other metal except platinum. The radioactive isotope cobalt-60 is widely used in radiation therapy.

Copper (Cu, 29) An attractive, corrosion resistant, reddish-brown transition metal (Group 1B) widely used on account of its high electrical and thermal conductivity and its ability to form strong, corrosion-resistant alloys, such as bronze (with tin), brass (with zinc) and cupronickel (with nickel). Found native and in sulphides, oxides and carbonates, copper is widely distributed. (See page 196.)

Curium (Cm, 96) Artificial, highly radioactive transuranium element made by bombarding plutonium with accelerated helium ions.

Dysprosium (Dy, 66) One of the rare-earth metals (transition Group 3B), whose compounds are sometimes used as catalysts. It has interesting magnetic properties. Below -168°C it becomes ferromagnetic, like iron; at really low temperatures it becomes superconductive.

Einsteinium (Es, 99) Artificial, short-lived, radioactive transuranium element made by irradiating uranium-238 with neutrons. It was first discovered in the debris from the first thermonuclear (H-bomb) explosion in 1952, and was synthesized two years later.

Erbium (Er, 68) One of the rare-earth elements (transition Group 3B), many of whose compounds are pink, including the rose pink oxide Er_2O_3 . At very low temperatures it is ferromagnetic and superconductive.

Europium (Eu, 63) The lightest and softest of the rare-earth elements (transition Group 3B), it is also one of the least abundant. Many of its salts are coloured. It readily absorbs neutrons and has potential applications in the nuclear energy field.

Fermium (Fm, 100) Artificial, radioactive transuranium element, obtained by bombarding uranium-238 with neutrons. Like einsteinium, it was first discovered in the debris from the first H-bomb, and subsequently synthesized.

Fluorine (F, 9) A greenish-yellow choking gas which is the first member of the halogen family (Group 7A) and the most reactive of all the elements. It combines with every other element except the rare gases helium, neon, and argon to form fluorides. It occurs widely in mineral compounds, including *fluorite* (*fluorspar*) CaF_2 ; *apatite*, $\text{CaF}_2 \cdot 3\text{Ca}_3(\text{PO}_4)_2$; and *cryolite*, sodium aluminium fluoride, Na_3AlF_6 . Boron and antimony fluorides are important catalysts; sodium fluoride is added to drinking water to help reduce tooth decay (fluoridation); uranium hexafluoride is used in separating uranium isotopes. Fluorine reacts with hydrocarbons to form fluorocarbons, including the 'non-stick' plastic, Teflon, which is polytetrafluoroethylene (CF_2CF_2)_n; and Freon, dichlorodifluoromethane (Cl_2CF_2), a refrigerant. (See page 231.)

Francium (Fr, 87) Rare radioactive element which is the heaviest of the alkali metals (Group 1A). It occurs transiently during radioactive decay of actinium. Only a few grams are present in the Earth's crust at any moment. Its properties resemble those of caesium.

Gadolinium (Gd, 64) A typical rare-earth metal (Group 3B) found with many others in the mineral *monazite*. Its salts and solutions are colourless. It becomes ferromagnetic at temperatures of 17°C and below, and at very low temperatures becomes superconductive. It absorbs neutrons more readily than any other element.

Gallium (Ga, 31) A soft metal of the boron group (Group 3A) which melts at just above room temperature (at 29.8°C). Once called eka-aluminium, it has somewhat similar chemical properties to aluminium. Its compounds occur sparsely in Nature, and it is extracted as a by-product from ores such as zinc blende and bauxite. Like aluminium it is amphoteric, reacting with both acids to form salts and alkalis to form gallates. With phosphorus, arsenic and antimony, gallium forms compounds that are semiconductors—gallium arsenide in particular is widely used.

Germanium (Ge, 32) A rare semi-metallic element (Group 4A) which, like its sister element silicon, has valuable semiconductor properties. Among its important compounds are the oxide, GeO_2 , and the tetrachloride, GeCl_4 . Zinc germanate, Zn_2GeO_4 , is used as a phosphor in fluorescent lamps. Germanium is extracted from certain ores, such as *germanite*, and can sometimes be recovered from flue dust—for many coals contain tiny amounts of the element.

Gold (Au, 79) Bright yellow, unreactive precious metal (transition Group 1B), which conducts heat and electricity superbly, and which is the most malleable and ductile of all metals. It occurs native and is widely mined. One of its important industrial uses is for plating contacts in printed circuits and semiconductors. Of the acids only aqua regia—a mixture of concentrated hydrochloric and nitric acids—will dissolve it. (See page 199.)

Hafnium (Hf, 72) Transition metal (Group 4B) closely resembling zirconium in chemical properties. It is hard, malleable and ductile, and has excellent corrosion resistance. One of its main uses is in control rods for nuclear reactors. It occurs naturally as the oxide in zirconium minerals such as zircon and cyrtolite.

Hahnium (Ha, 105) A short-lived radioactive transuranium element, whose most stable isotope has a half-life of only a few seconds.

Helium (He, 2) The lightest element after hydrogen and first member of the inert gases (Group 0). It has the lowest boiling point of any element (-269°C), and in liquid form displays the phenomenon of superfluidity. It was discovered first in the Sun's atmosphere. After hydrogen, it is probably the most common element in the universe. It is synthesized from hydrogen during the nuclear fusion processes which produce stellar energy.

Holmium (Ho, 67) One of the least abundant of the rare earths (transition Group 3B), which forms yellowish-brown salts. It becomes ferromagnetic at very low temperatures (below -253°C).

Hydrogen (H, 1) The simplest and lightest of all elements, and the most abundant element in the universe. Chemically it bears certain resemblances to both the alkali metals (Group 1) and the halogens (Group

7). It forms hydrides with weak metals, as in tin hydride (SnH_4); and with non-metals, as in hydrogen fluoride and chloride (HF, HCl); nitrogen hydride, or ammonia (NH_3); and carbon hydride, or methane (CH_4). With carbon it forms an enormous range of organic compounds.

Indium (In, 49) Rare metal of the boron family (Group 3A), which is soft and plastic and like tin emits a 'cry' when bent. It was named after the indigo blue colour displayed by its compounds in the flame test. Its oxide, In_2O_3 , is yellow. It is used in bearing alloys to improve lubricant wetting characteristics and corrosion resistance. Its most important use is in the manufacture of semiconductor devices.

Iodine (I, 53) Soft, dark grey crystalline solid belonging to the halogen family (Group 7A). It sublimes at room temperature to give a deep violet irritating vapour. It occurs naturally in salt deposits and brine, as iodides, such as sodium iodide, NaI; and iodates, such as calcium iodate, $\text{Ca}(\text{IO}_3)_2$. It can also be extracted from seaweeds. Tincture of iodine—iodine dissolved in potassium iodide, KI, water and alcohol—is an excellent bactericide. Iodine combines with most metals and non-metals. Hydrogen iodide (HI) in solution is a strong acid, giving rise to salts—iodides. Iodic acid (HIO_3) gives rise to the iodates. (See page 232.)

Iridium (Ir, 77) Rare brittle metal of the platinum group (transition Group 8B) which is one of the hardest and densest pure metals known (relative density 22). It finds its greatest use in alloys with platinum, and gives that metal greater chemical resistance. It is obtained in alloys with other platinum metals as a by-product of nickel and copper refining.

Iron (Fe, 26) A weak, corrosion-prone transition metal (Group 8B) that can be transformed by the addition of small amounts of alloying materials, particularly carbon, into our most important metal, steel. It is the fourth most abundant element and the second most abundant metal (after aluminium) in the Earth's crust, where it occurs as oxides, such as haematite (Fe_2O_3) and magnetite (Fe_3O_4); sulphides, such as pyrites (FeS); and carbonates, such as siderite (FeCO_3). One of iron's most distinctive properties is its magnetism. Like many transition metals, iron forms complex ions, such as hexacyanoferrates (ferricyanides), as in the potassium salt, $\text{K}_3\text{Fe}(\text{CN})_6$. (See page 191.)

Krypton (Kr, 36) One of the inert gases (Group 0); found in small traces (about one part per million) in the atmosphere. It is used to fill some electric tubes and fluorescent lamps.

Lanthanum (La, 57) The first member of the lanthanide series of rare-earth metals (Group 3B)—fifteen metals with very similar chemical and physical properties. Lanthanum is found with other rare earths in monazite and other minerals. The alloy, misch metal, which is used for lighter flints, contains 25% lanthanum.

Lawrencium (Lw, 103) The eleventh transuranium element, named after the inventor of the cyclotron, Ernest Lawrence. It is made by bombarding californium with accelerated boron ions.

Lead (Pb, 82) A soft, heavy metal related to tin (Group 4A). Easy to shape and resistant to corrosion, it has been used for making water pipes for thousands of years. Today its greatest use is in car batteries, though it is widely used elsewhere in numerous alloys. Its soluble compounds are poisonous. (See page 202.)

Lithium (Li, 3) The first of the alkali-metal group (Group 1A) and the lightest of all solid elements (relative density 0.53). A soft, silvery white metal of low melting point (180°C), it is used in some lightweight alloys. Like all the alkali metals, it decomposes water, liberating hydrogen. (See page 205.)

Lutetium (Lu, 71) Last member of the rare-earth metals (Group 3B), of which it is the hardest and densest and has the highest melting point. It is of little use.

Magnesium (Mg, 12) A light alkaline-earth metal (Group 2A), it is widely used in the aerospace industries in alloys with aluminium and other metals. It burns brilliantly in air to form pure white magnesium oxide. It occurs widely, for example, as the carbonate magnesite and the double carbonate with calcium, dolomite. (See page 207.)

Manganese (Mn, 25) A hard transition metal (Group 7B), whose main use is in steelmaking. Manganese absorbs impurities from the steel and strengthens it. High manganese steel has exceptional hardness and wear resistance. Important manganese compounds include the oxide, which is a good catalyst, and potassium permanganate, an excellent oxidizing agent. Manganese has oxidation states of 2+ in salts, 6+ in manganates and 7+ in permanganates.

Mendelevium (Md, 101) Artificial radioactive element of the actinide series, obtained by bombarding einsteinium with helium ions. Relatively short-lived, its most stable isotope has a half-life of only two months.

Mercury (Hg, 80) The only metal that is liquid at room temperature, mercury is related to zinc and cadmium (Group 2B). Often called quicksilver, mercury is used in barometers and thermometers; and as vapour in discharge tubes and vacuum pumps (mercury diffusion pumps). It forms alloys called amalgams with most metals (but not iron); silver and gold amalgams are used to fill teeth. It forms mercury (I) compounds (e.g. calomel, Hg_2Cl_2) and mercury (II) (e.g. HgCl_2). Both chlorides have medical uses. The main source of mercury is cinnabar (HgS).

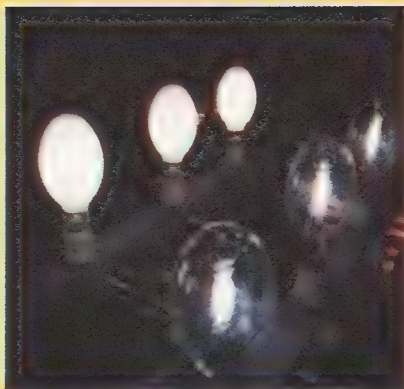
Molybdenum (Mo, 42) A transition metal (Group 6B) which is alloyed with steel to impart high-temperature strength. It has a high melting point (2620°C) and retains its hardness and strength at high temperatures. One of its most useful compounds is the disulphide MoS_2 , which has a layered structure (like graphite), and is a lubricant.

Neodymium (Nd, 60) The third most plentiful of the rare-earth metals (Group 3B). Found in the mineral monazite, it is a constituent of the alloy, misch metal (for lighter flints), and is used to colour ceramic glazes and glasses.

Neon (Ne, 10) One of the most useful of the rare gases (Group 0), neon is used in discharge tubes. Neon tubes emit a brilliant orange-red light. Neon is obtained by distilling liquid air.

Neptunium (Np, 93) An artificial radioactive element following uranium (which it resembles) in the Periodic Table. It is obtained by bombarding uranium with slow neutrons. Its most stable isotope has a half-life of more than 2 million years.

Nickel (Ni, 28) A tough, hard silvery white transition metal (Group 8), which has excellent corrosion resistance. Its alloy with copper, cupronickel, is used for our 'silver' coinage. It is widely used for plating, in stainless steels, and as a catalyst. One of its most interesting compounds is the volatile carbonyl, $\text{Ni}(\text{CO})_4$. Being ferromagnetic, nickel is a major ingredient of magnet alloys. (See page 198.)



Above: Mercury vapour lamps being tested.

Below: Loading liquid nitrogen (-196°C).



Niobium (Nb, 41) A soft, ductile metal closely related to tantalum (Group 5B) with which it occurs in ores such as columbite. (It was once called columbium.) A major use is in superconductors.

Nitrogen (N, 7) A colourless, tasteless, and odourless gas (Group 5A), nitrogen is the major constituent of air (78% by volume). It is an important constituent of the proteins in living matter. It occurs in Nature as nitrates, such as Chile saltpetre, NaNO_3 ; as ammonium compounds, such as NH_4Cl . It forms a whole series of oxides, including laughing gas, N_2O . (See page 215.)

Nobelium (No, 102) An artificial radioactive element made by bombarding curium with carbon ions. The most stable isotope has a 3-month half-life.

Osmium (Os, 76) A hard, brittle metal that has a greater density (relative density 22.5) than any other. One of the platinum metals (Group 8), it has an exceptionally high melting point (3000°C). It is used chiefly as a hardener in platinum alloys. (See page 201.)

Oxygen (O, 8) The life-giving gas in air of which it makes up 21% by volume. It is the most abundant element (Group 6A) in the Earth's crust, of which it makes up 46.6%. It combines with most other elements to form oxides, such as water (H_2O), carbon dioxide (CO_2), silicon dioxide (SiO_2), iron oxides (Fe_2O_3 , Fe_3O_4) and aluminium oxide, bauxite (Al_2O_3). Liquid oxygen, obtained by distilling liquid air, is used as a rocket propellant and explosive. (See page 216.)

Palladium (Pd, 46) A ductile, corrosion-resistant transition metal (Group 8) similar to platinum. It is used as a catalyst, and to make jewellery and electrical contacts. (See page 201.)

Phosphorus (P, 15) A waxy, solid element of the nitrogen family (Group 5A) which glows in the dark. It bursts into flame on contact with air. An essential ingredient in living matter, phosphorus occurs in teeth and bones as calcium phosphate. There are four allotropes of phosphorus—white, red, violet and black, in order of reactivity. (See page 229.)

Platinum (Pt, 78) A heavy, soft, ductile and corrosion-resistant transition metal (Group 8) with high melting point (1769°C). Its main use is in jewellery and as a catalyst. It has a high electrical resistance, which varies with temperature. This property is used in the platinum resistance thermometer. (See page 201.)

Plutonium (Pu, 94) An artificial radioactive element made by bombarding uranium-238 with neutrons. It is the most important of the transuranic elements because its isotope Pu-239 is fissile, and can therefore be used as fuel in nuclear reactors (see page 30). Plutonium wastes from nuclear reactors pose a serious pollution threat because they are deadly poisons and they have a long half-life (24,000 years).

Polonium (Po, 84) A naturally-occurring radioactive metal (Group 6A) found in traces in pitchblende and other uranium minerals. The most common isotope has a half-life of 138 days.

Potassium (K, 19) One of the soft, reactive alkali metals (Group 1A) closely resembling sodium in chemical properties. It was the first metal to be isolated by electrolysis (by Humphry Davy, 1807). (See page 205.)

Praseodymium (Pr, 59) A yellowish rare-earth metal (Group 3B) which forms greenish salts. It is used to colour ceramics, in lighter flints, and in some lightweight alloys.

Promethium (Pm, 61) A radioactive rare-earth element (Group 3B) produced during nuclear fission of uranium and by bombarding neodymium with neutrons. It has typical rare-earth properties, and most of its compounds are pink.

Protactinium (Pa, 91) A very rare naturally-occurring radioactive metal preceding uranium in the Periodic Table. Traces of it occur in all uranium ores. The most stable of its 12 isotopes has a half-life of 33,000 years.

Radium (Ra, 88) A heavy, rare, radioactive alkaline-earth metal (Group 2A), first isolated in 1910 by Madame Curie. It results from the decay of uranium, and is found in uranium ores such as pitchblende. The penetrating rays given off by radium are used in cancer therapy. The most stable radium isotope has a half-life of 1600 years.

Radon (Rn, 86) The heaviest of the inert rare gases (Group 0), which is formed when radium decays. Like radium, it is radioactive. Traces of radon appear in the air, but in hardly detectable concentrations. Even the most stable of its 17-odd isotopes has a half-life of only 4 days.

Rhenium (Re, 75) A very rare and expensive transition metal (Group 7B) with exceptional hardness and resistance to wear and corrosion. It also has a very high density (relative density 21) and its melting point (3180°C) is the highest of all metals except tungsten. It is found naturally in the molybdenum ore, molybdenite, and in other sulphide ores.

Rhodium (Rh, 45) One of the precious platinum family of transition metals (Group 8). Ductile and corrosion-resistant, it is often plated on to silver to prevent tarnishing. It is added to platinum as a hardener. (See page 201.)

Rubidium (Rb, 37) A soft alkali metal (Group 1A) of similar properties to sodium, which will burn in air and decompose water.

Two isotopes occur in Nature. One, Ru-87, is radioactive, with a 50,000 million year half-life; it decays to strontium-87. One form of radiometric dating uses the rubidium-strontium decay. (See page 205.)

Ruthenium (Ru, 44) A hard, brittle transition metal (Group 8) of high melting point related to platinum. It is alloyed with platinum to harden it. (See page 201.)

Rutherfordium (Ru, 104) The name suggested for the transuranium element 104 by American physicists. Russian physicists, who claim to have made it in 1964, five years before the Americans, call it kurchatovium.

Samarium (Sm, 62) A rare-earth metal (Group 3B), obtained from the mineral monazite. It has uses in ceramics and electronics and as a catalyst in the chemical industry. Its salts are red to yellow.

Scandium (Sc, 21) The first member of the first transition series of metals (Group 3B). A rare-earth metal, it was first identified in Scandinavian ores containing other rare earths. Traces of scandium are also found in tin and tungsten ores. Many stars, including the Sun, contain appreciable amounts of scandium.

Selenium (Se, 34) A metalloid belonging to the oxygen family of elements (Group 6A) and related chemically to sulphur and tellurium. It often occurs as the selenide with the sulphide ores of lead, silver, and copper. It can be obtained from the flue dust when these ores are roasted, or from the slime at the anode in electrolytic refining. Of its many different forms, the most important is the metallic. The metallic form is used in photoelectric devices because it emits electrons when light strikes it.

Silicon (Si, 14) The most abundant element (27.7%) in the Earth's crust after oxygen, silicon is a non-metal closely related to carbon (Group 4A). It occurs almost everywhere in the crust as silicates, such as feldspar, KAlSi_3O_8 , or as the dioxide, silica or crystalline quartz, SiO_2 . Pure silicon is a hard, metallic-looking solid with the crystal structure of diamond. Adulterated with traces of other elements, silicon becomes a semiconductor. Minute silicon chips form the basis of the large-scale integrated (LSI) circuits used in many solid-state electronic devices, such as pocket calculators. Silicon is also used to make the solar cells which provide spacecraft with electricity.

Silver (Ag, 47) A precious metal related to copper and gold (Group 1B). Its beautiful whiteness, the ease with which it can be shaped, and its resistance to most corrosion led to its use in jewellery, for coins, and for expensive tableware. The scientist prizes it because it conducts heat and electricity better than any other element. Many of its salts are light-sensitive. (See page 199.)

Sodium (Na, 11) A soft, alkali metal (Group 1A) which is the sixth most abundant (2.80%) element in the Earth's crust. One of the most widespread sodium compounds is the chloride, common salt (NaCl). One of the most reactive of all elements, sodium decomposes water to yield sodium hydroxide, or caustic soda (NaOH), which is a strong alkali. (See page 205.)

Strontium (Sr, 38) An alkaline-earth metal (Group 2A) whose compounds colour a flame a characteristic crimson. It occurs in minerals such as the carbonate strontianite (SrCO_3) and the sulphate celestite (SrSO_4). It closely resembles calcium (see page 207).

Sulphur (S, 16) A non-metallic element related to oxygen (Group 6A), sulphur is one of the few elements that can be found native in the Earth's crust. It also occurs in the form of metal sulphides—those of iron

(FeS), lead (Pbs), and zinc (ZnS), for example; and as sulphates, such as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). The most important chemical made from sulphur is sulphuric acid, H_2SO_4 —the 'life-blood' of industry. (See page 230.)

Tantalum (Ta, 73) A very hard, acid-resisting heavy metal with an extremely high melting point (3000°C). It is a transition metal (Group 5B) closely related to niobium. It occurs with that metal in the columbite-tantalite series of minerals. Its main uses are in capacitors and in corrosion-resistant chemical equipment.

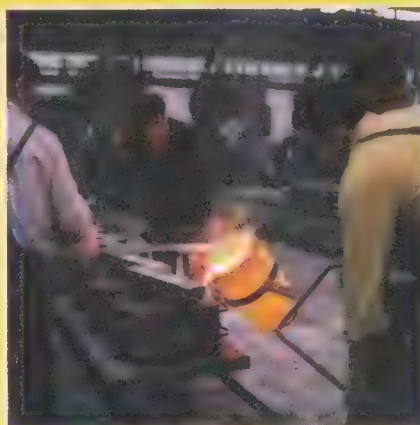
Technetium (Tc, 43) A radioactive transition element (Group 7B), which was the first element to be produced synthetically by nuclear bombardment. Large quantities of technetium are now produced in nuclear reactors as products of nuclear fission.

Tellurium (Te, 52) A metalloid in the oxygen group (Group 6A) which closely resembles selenium. It is obtained as a by-product of lead, gold and copper refining, occurring in the ores as a telluride. It is occasionally used in alloys, and in semiconductors—such as bismuth telluride.

Terbium (Tb, 65) One of the rarest of the rare-earth metals (Group 3B), it is sometimes used in lasers and semiconductors.

Thallium (Tl, 81) A soft metal (Group 3A) whose physical properties closely resemble those of lead, which follows it in the Periodic Table. Its compounds are very poisonous.

Thorium (Th, 90) A naturally occurring radioactive metal of the actinide series (Group 3B). Occurring in such minerals as monazite and thorite, thorium is three times more abundant than uranium. In breeder reactors the isotope Th-232 will change into uranium-233, which is fissile. The dioxide, ThO_2 , is an important industrial refractory.



Above: A silicon carbide crucible.

Below: Mining salt underground.



Thulium (Tm, 69) A fairly rare rare-earth metal (Group 3B). Its short-lived radioactive isotope, Tm-170, is sometimes used as a portable X-ray source since it emits soft gamma-radiation resembling X-rays.

Tin (Sn, 50) A soft, ductile corrosion-resistant metal of the carbon family (Group 4A). It is widely used as plating on mild steel, as tinplate, and in many alloys, including solder, bronze, type metal and pewter. It occurs in two allotropic forms—white and grey. The familiar form is white which, when pure, changes into the powdery grey form at low temperatures. Impure commercial tin does not usually undergo such a change. (See page 202.)

Titanium (Ti, 22) A strong, light transition metal (Group 4B) which has excellent corrosion resistance. It is widely used in the aerospace industries. It is also used in surgical aids. The ninth most abundant element, it is found in the minerals, ilmenite and rutile. Rutile—titanium dioxide—is an important white paint pigment. (See page 204.)

Tungsten (W, 74) Also called wolfram; a very strong, brittle, transition metal (Group 6B) which has the highest melting point among metals (3380°C). It is incorporated in steel to increase high-temperature strength. Tungsten wire is used for electric-light bulb filaments. Tungsten carbide is used for making very hard, tough tools and dies. (See page 204.)

Uranium (U, 92) A naturally occurring radioactive heavy metal of the actinide series (Group 3B). Natural uranium is made up mainly of the isotope U-238, but with traces of U-235 and U-234. U-235 has the property of undergoing fission, which makes possible commercial nuclear power. (See page 16.)

Vanadium (V, 23) A rare, soft transition metal (Group 5B) whose main use is in alloy steels. It improves the steel's hardness, strength and shock resistance. It was named after the Scandinavian goddess of beauty, for solutions of its compounds display beautiful colours. Vanadium pentoxide is an important catalyst, used, for example, in sulphuric acid manufacture by the contact process.

Xenon (Xe, 54) A very rare inert gas (Group 0), more than four times as heavy as air. It is used in high-intensity flash lamps. It was the first inert gas to be made to combine chemically with other elements. The first compound formed was the red solid xenon hexafluoroplatinate.

Ytterbium (Yb, 70) A soft rare-earth metal (Group 3B) which forms pale green or white salts. It is scarce, expensive and little used.

Yttrium (Y, 39) An abundant rare-earth metal (Group 3B) found in such rare-earth ores as xenotime and gadolinite. Yttrium compounds are used in ceramics, in lasers, and in red phosphors for colour television. A common phosphor is yttrium orthovanadate, activated by europium.

Zinc (Zn, 30) A common metal related to cadmium and mercury (Group 2B). Mixed with copper, it forms the important alloy brass; it is coated on steel to prevent rusting (galvanizing). It is the negative pole in dry batteries. Its most important commercial ore is zinc blende, or sphalerite, ZnS . (See page 202.)

Zirconium (Zr, 40) A soft, ductile, corrosion-resistant transition metal (Group 4B) related to titanium. Its major use is for cladding fuel rods in nuclear reactors. It has low neutron absorption, and remains strong at high temperatures. Its oxide, zirconia, is an excellent refractory. Naturally-occurring crystalline zirconium silicate is the gemstone zircon.

Minerals

With only a few exceptions, the chemical elements are too reactive to be found *native*, or uncombined, in the Earth's crust. Instead they are found combined with each other in definite and unchanging proportions in the form of *minerals*. In all, about 3,000 minerals are known. Two only—mercury and water—are liquids; the remainder are solids. Among the most common minerals are calcite (calcium carbonate, CaCO_3), quartz (silicon dioxide, SiO_2), haematite (iron oxide, Fe_2O_3), salt (sodium chloride, NaCl), magnesite (magnesium carbonate, MgCO_3), gypsum (calcium sulphate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), pyrites (iron sulphide, FeS_2) and feldspar (potassium aluminium silicate, KAlSi_3O_8).

It is no coincidence that oxygen appears in all but two of the above minerals. Oxygen is the most common of all the elements in the Earth's crust, accounting for no less than 46.6% by weight. Silicon is the next most common element, accounting for some 27.7%. Then, in order, come aluminium (8.1%), iron (5.1%), calcium (3.6%), sodium (2.8%), potassium (2.6%) and magnesium (2%). Together these eight elements make up 98% of the Earth's crust. The eighty-four remaining natural elements make up the other 2%.

The types of chemical combination represented in the mineral kingdom—oxides, sulphides, halides, sulphates, carbonates, and silicates—provides a convenient means of classifying minerals. Of the minerals the most important are the *ores*. These are metallic minerals which can be processed profitably to yield the metal. The word 'profitably' is important here. Bauxite, which contains aluminium oxide, is the ore of aluminium. It is not the most common aluminium-bearing mineral. Feldspar, which contains aluminium, is much more common—in fact it is the commonest mineral of all. But there is no economic way of processing feldspar to obtain the aluminium, so it is not an ore.

Although the metallic ores are the most important class of minerals, a wide variety of non-metallic minerals also have an important part to play in the modern world. These are minerals which contain non-metallic elements (such as sulphur, graphite and quartz), or those whose use does not depend on the presence of the metal in them (borax, gypsum, chalk, talc, halite). Gems are another type of mineral, whose rarity, beauty and hardness make them highly prized. Diamonds, emeralds, sapphires and rubies are the most sought-after gems. Although these can now be made synthetically, the artificial crystals cannot compete in quality with those found in Nature.

In general, minerals are scattered widely



but sparsely throughout the Earth's crust. Only in certain places have natural processes given rise to concentrated deposits of minerals. Extracting, or mining, these mineral deposits is one of the world's most vital industries. Mining, however, is a wasting process. Once the supply of minerals in the Earth's crust has gone, it has gone for good. It has been estimated that by the year 2100, ores of the following metals will have been exhausted: lead, platinum, gold, silver, uranium, copper, tungsten, manganese, cobalt, and aluminium.

Mineral Characteristics

In general there is no simple way of identifying a particular mineral, because the same mineral can appear in different guises. Quartz, for example, occurs in a variety of shapes and in a variety of colours. Shape and colour alone therefore serve no useful purpose. But if we add to them other characteristics, such as hardness and cleavage, we can build up an accurate picture of the mineral.

One important mineral characteristic is crystal form. Under suitable conditions minerals grow in the form of crystals, whose geometric shapes are related to the internal structure of the mineral. Among the many crystal forms are the cube (6 faces, e.g. galena, rock salt), rhombohedron (6 faces, e.g. dolomite), octahedron (8 faces, e.g. diamond), rhombic dodecahedron (12 faces, e.g. garnet), icositetrahedron (24 faces, e.g. pyrites). These are variations of certain basic crystal systems of which there are seven in all: cubic, tetragonal, hexagonal, trigonal, orthorhombic, monoclinic, and triclinic. Sometimes *twinning* occurs in crystals. A twin crystal consists of two or more crystals with a different orientation. The

Drilling the shot holes in a lead-zinc mine at Kimberley, British Columbia, Canada, with a diamond-tipped drill. After drilling, the holes are filled with explosive. The explosives are fired in a certain order to have maximum effect. The minerals in the ore are zinc blende (also called sphalerite) and galena, being zinc sulphide and lead sulphide respectively. Silver is obtained as a by-product in processing the Kimberley ores.





Like many metals, lead is obtained from its ores by smelting in a furnace. The picture shows impurities burning out of the molten lead during refining operations.



twins may be *interpenetrant*—they may penetrate each other; they may be *geniculate*, or knee-shaped; or they may be mirror-image, *rotation* twins.

A property related to crystalline form and structure is *cleavage*. This is the tendency of the mineral to cleave, or split, along certain planes. In general these are parallel to potential crystal faces. Mica, for example, cleaves into thin parallel sheets.

Mica sheets have a typical pearly appearance in reflected light. This property, known as *lustre*, is another characteristic of many minerals that aids identification. Quartz has a typical vitreous, or glass-like lustre; sulphur and zinc blende, a resinous lustre; fibrous asbestos, a silky lustre; some lead minerals, an adamantine, or diamond-like lustre. Many metallic minerals, including pyrites and galena, have a typical metallic lustre.

Many minerals leave a distinctive coloured *streak* when rubbed on strong paper or a tile. With hard minerals it may be necessary to scratch the surface to obtain a powder, and crush the powder to obtain a streak.

Relative density and *hardness* are other physical properties which aid mineral identification. Some minerals are noticeably heavy—cassiterite (tin oxide), for example, has a relative density of 7—more than double that of most minerals. Barytes, with a relative density of 4.5, is known as heavy spar. Hardness is assessed according to a scale of hardness devised by the German mineralogist Friedrich Mohs. He arranged 10 common minerals in order of increasing hardness to form a standard against which other minerals could be compared. He chose talc for the softest mineral, No. 1, and diamond for the hardest mineral, No. 10. The whole Mohs scale is:

No.	Mineral	Comments
1	Talc	Crushed by fingernail
2	Gypsum	Scratched by fingernail
3	Calcite	Scratched by bronze coin
4	Fluorite	Scratched by glass
5	Apatite	Scratched by penknife
6	Feldspar	Scratched by quartz
7	Quartz	Scratched by hard steel file
8	Topaz	Scratched by corundum
9	Corundum	Scratched by diamond
10	Diamond	Scratched only by itself

Each mineral in the scale can scratch the one below it and be scratched by the one above it. Corundum will scratch topaz, for example, and will be scratched by diamond. A few rough-and-ready comparisons can be used. A fingernail has a hardness midway between gypsum and calcite, that is, about $2\frac{1}{2}$; a bronze coin, about 3; glass, about 5; a penknife blade, about 6; and a hard steel file about 7. In some crystals the hardness may vary from face to face. In crystals of the silicate mineral kyanite, for example, the hardness varies between 4 and 7.

A few minerals have magnetic and electrical properties. The iron oxide magnetite can be attracted by a magnet. One form of magnetite,

called lodestone, is a natural magnet. Minerals containing cobalt and nickel also respond to a magnetic field. Some mineral crystals, including quartz, will acquire an electric charge when pressure is applied to them. They are called *piezoelectric*. There are also *pyroelectric* crystals, which acquire a charge when heated; tourmaline is an example.

Fluorescence is a characteristic that expedites the identification of certain minerals, such as fluorite from which the effect takes its name. When a fluorescent mineral is irradiated with ultra-violet light, it emits coloured light. The colour of the light emitted is seldom the same as that of the emitting mineral. Fluorescence is one type of *luminescence*. Other types are cathodoluminescence, light emission caused by irradiation with accelerated electrons; thermoluminescence, light emission caused by heating; and triboluminescence, light emission caused by mechanical deformation.

Formation of Minerals

Most minerals have their origin in the molten rock, or magma, beneath the Earth's crust. When this magma rises through the crust, it cools. The minerals it contains begin to crystallize, and eventually it sets solid as *igneous rock*. A typical rock consists of a tightly knit mass of a variety of crystals. If the magma cools slowly, the mineral crystals have time to grow quite large, and a coarse-grained rock such as granite is produced. If cooling is more rapid, however, the crystals have little time to grow, and a fine-grained rock like basalt is formed.

In general, the minerals in rocks are so mixed together and scattered that they can seldom be extracted profitably. But in some places natural processes have resulted in minerals being concentrated into workable deposits. Sometimes concentration occurs in the magma itself, when heavy minerals (such as magnetite and chromite) settle out under the influence of gravity to form so-called *segregations*. As consolidation of the magma into rock nears completion, highly mobile mineral-rich liquids and gases leave the magma and thrust towards the surface through fissures in the rocks.

These fluids, called hydrothermal solutions, crystallize progressively as they cool. The fissures become infilled, forming *veins* or *lodes*. The crystallizing minerals usually form layers parallel to the walls of a fissure. Where a fissure is not completely filled, the mineral crystals have room to develop further. The majority of the most beautiful mineral crystals have been found in such cavities, or *vugs*. Sometimes the mineral-rich solutions coming from the magma destroy the rocks with which they come into contact and then replace them. Replacement may be complete, or it may be selective, with only certain constituents of the rock being replaced. The replacement minerals are consequently scattered throughout the host rock.

When a mineral lode outcrops at the



surface, it often suffers chemical weathering and its mineral content passes into solution. The solution percolates downwards until, under suitable conditions, the mineral is deposited from it, forming a *zone of secondary enrichment*. Copper lodes containing chalcoppyrite (copper pyrites) are commonly subject to this form of concentration. Surface water may dissolve some of the minerals in the rocks as it flows over them. The water eventually finds its way to the sea. In time the sea becomes saturated with the mineral. It is then precipitated and sinks to the seabed. When the

Galena crystals with smaller calcite crystals. Galena, or lead glance, is the main ore of lead, consisting of lead sulphide.

seabed is uplifted by geological action or the surface waters evaporate, the mineral deposits remain. The great Stassfurt deposits in Germany and the salt flats of Utah, USA, were formed in this way. Sometimes these minerals or salt deposits become compressed into massive sedimentary rocks. Gypsum and halite (common salt) are common examples.

Weathering of rocks containing heavy minerals, such as gold, diamonds, and cassiterite, often gives rise to *placer* deposits. Alluvial placers are formed when weathered particles are transported by stream action. The heavy minerals tend to settle in the stream bed, while lighter material is washed away. Eluvial placers are deposits formed on downhill slopes without the action of flowing water. Waves pounding mineral-rich beaches have a sorting action and may give rise to valuable placer deposits.

Metamorphism within the Earth's crust also often results in the formation of deposits of certain valuable minerals, including asbestos, garnet, and talc. It involves the change of existing igneous or sedimentary rocks into new ones of different mineral or crystal type. The change is brought about by contact of the existing rock with fresh, hot magma and by interaction with mineral-rich liquids and gases emanating from the magma. This contact metamorphism produces a relatively narrow zone of change. More widespread, regional metamorphism is a result of the action of heat and pressure caused by massive crustal movements during mountain building.



A fine example of a gem opal. The reddish-orange colour is characteristic of the variety of opal called fire opal. Precious opals are usually given a smoothly rounded finish, which best displays the opalescence, or play of colour, of the stone. In classical times the opal was ranked among the noble gems. Chemically opal is a form of hydrated silica. The milkiness of some opals is caused by the presence of minute gas bubbles. Most gem opals are translucent to transparent. Their colour results from traces of metal oxides.

Chemical Reactions

Chemical changes, or reactions, are not confined to the chemist's laboratory. They take place all the time, everywhere. Burning of fuel involves a chemical change, so does the rusting of metal, the fermentation of wine, the digestive process in animals, and the making of food by plants. In each case one or more substances, the *reagents*, change into other substances, the *products*, which have different properties. For example, when the hydrocarbon fuel methane is burned, it changes into carbon dioxide and water. It is oxidized by the oxygen in the air.

The Basic Reactions

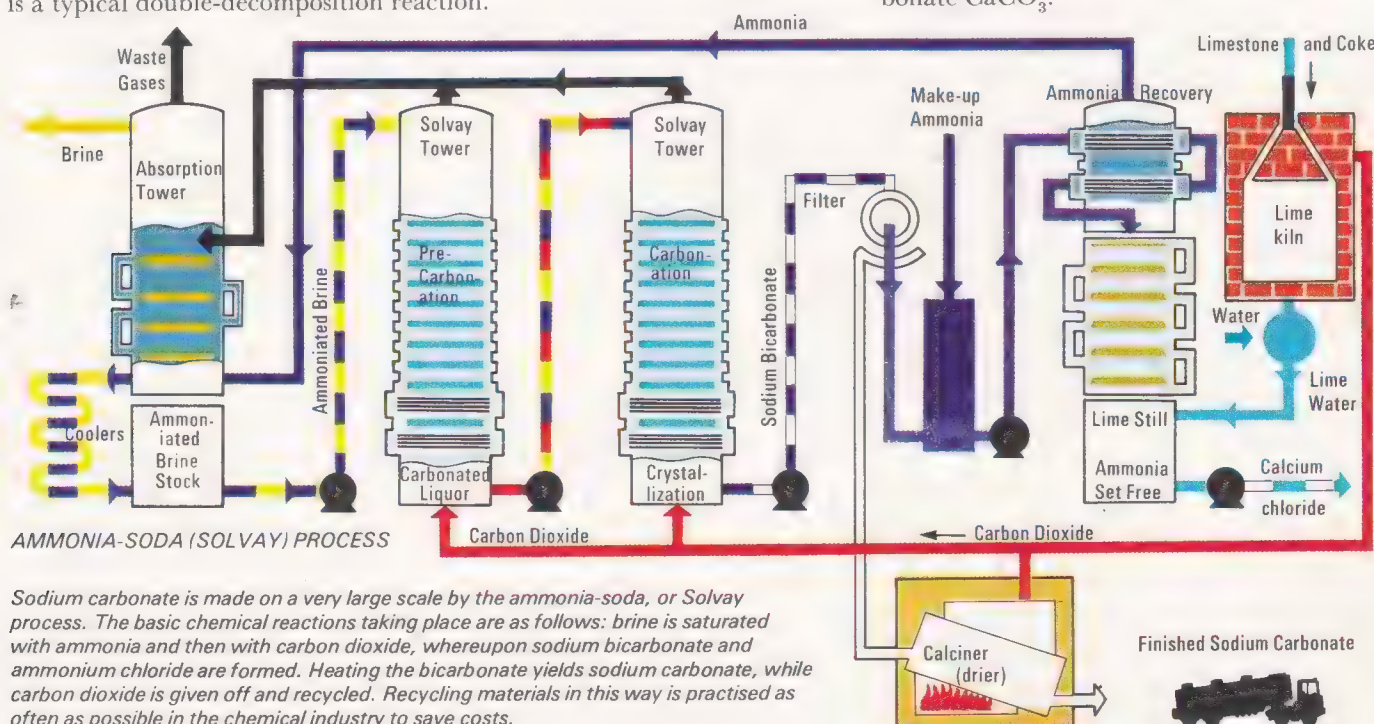
Oxidation by the oxygen of the air is one of the commonest chemical reactions. It is an example of simple chemical combination, or *synthesis*, of one element with oxygen. The oxidation of hydrogen to give water and the union of hydrogen and chlorine to form hydrogen chloride are typical examples of simple chemical combination. Another common type of chemical reaction is *decomposition*, in which a compound is broken down to yield two or more simpler substances. The break-up of chalk into carbon dioxide and quicklime (calcium oxide) on heating is an example of chemical decomposition.

The most common chemical reaction, however, is *double decomposition*. It involves the reaction of two chemical compounds to form two different compounds. The combination of an acid and a base to form a salt and water is a typical double-decomposition reaction.

Nine different kinds of catalysts used in the chemical industry. They are, from bottom left to top right: platinum on an alumina support; iron oxide; cobalt molybdate; iron oxide; zinc and chromium oxides; zinc; cobalt molybdate; copper and zinc oxides; and nickel. The iron oxide is used, for example, during the Haber synthesis of ammonia. The zinc and chromium oxides are used for the synthesis of methanol from carbon monoxide and hydrogen.



When a chemical change takes place, the atoms in the reacting molecules are regrouped to form new molecules. This can be represented by a chemical equation, using symbols for each atom. The formula of a molecule is made up of symbols of the atoms it contains with a subscript to denote the number of atoms. For example, the formula for a molecule of hydrogen is H_2 and that of calcium carbonate is $CaCO_3$.



Here are the chemical equations for three of the basic chemical reactions mentioned above, with the reagents on the left and the products on the right. First, the simple combination of hydrogen and chlorine to form hydrogen chloride:

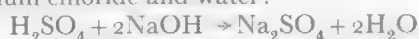


Since atoms are neither created nor destroyed, the number of atoms on each side of the equation must balance. Hence the need for the 2 before the HCl. This signifies that 2 molecules of hydrogen chloride result from the union of one molecule of hydrogen and one molecule of chlorine.

Secondly, the decomposition of calcium carbonate into quicklime and carbon dioxide:



Thirdly, the double decomposition of sulphuric acid and sodium hydroxide to give sodium chloride and water:



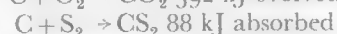
A balanced equation also describes the quantitative relationship between the reagents taking part in the chemical reaction. We simply add up the weights of all the atoms (atomic weights). For the decomposition shown above, $40 + 12 + (3 \times 15) = 100$ parts of CaCO_3 yield $40 + 16 = 56$ parts of CaO and $12 + (2 \times 16) = 44$ parts of CO_2 . So we can say that 100 grams of calcium carbonate will decompose to give 56 grams of quicklime and 44 grams of carbon dioxide.

Heat and Chemical Reactions

In a chemical reaction, when matter undergoes a transformation, energy is invariably liberated or absorbed. This energy is the difference between the energy required to break the chemical bonds holding the reagent molecules together and the energy liberated

as new bonds form in the product. If the latter exceeds the former, the reaction will release energy overall. If the reverse is true, the reaction will absorb energy overall.

When carbon burns in air to form carbon dioxide, energy in the form of heat is given out, and the reaction is said to be *exothermic*. When carbon reacts with sulphur to form carbon disulphide, heat is absorbed, and the reaction is said to be *endothermic*. The amount of heat absorbed or liberated in the formation of one mole (gram-molecule) of a substance from its elements is called the *heat of formation*. It is measured in kilojoules, or kJ. The reactions mentioned above can be represented by the equations



The heat liberated or absorbed during a chemical reaction is influenced by several factors, notably the physical state of the reagents and products. When hydrogen is combined with oxygen to form water, for example, the overall heat change depends on whether the water is liquid or steam. The heat liberated when steam condenses—the latent heat—must be taken into consideration. If the reactions take place in solution, the heats of solution of the reagents and products must be allowed for in thermochemical calculations. A notable example of a substance with a large heat of solution is sulphuric acid. It releases 84 kilojoules per mole when it dissolves in water.

Catalysts

Another important factor in a chemical reaction is the rate at which it proceeds. In a straightforward reaction the rate depends primarily on three things. One is the concentration of the reagents. All other things being equal, the rate of a reaction is directly proportional to the active masses of the substances resulting. This is called the *law of mass action*. (Active mass is the concentration in number of moles per litre, raised to the power of the number of molecules.) So, if you increase the concentration of the reagents in a chemical reaction, you increase the reaction rate.

A reaction is also accelerated by an increase in temperature. Generally, the rate of a reaction that takes place relatively slowly at normal temperatures can approximately be doubled by a 10°C rise in temperature.

Some reactions are very sensitive to the presence of certain foreign substances. These substances may dramatically increase or decrease the reaction rate. When the rate of reaction is increased, the substance is termed a *catalyst*; when the rate is decreased, it is termed a *negative catalyst*. Catalysis is of great importance in chemistry for it often enables reactions to be carried out under less severe conditions of temperature and pressure than would otherwise be necessary. The laboratory preparation of oxygen uses the thermal decomposition of potassium chlorate. To decompose potassium chlorate by itself com-

Carefully placed high explosives quickly demolish buildings with the minimum of disturbance to neighbouring properties. Explosions are very rapid chemical reactions which produce large volumes of gas in a very short period of time. So-called high explosives generate very high pressure, and set off powerful shock waves which cause the damage. Low explosives by contrast can be regarded simply as fast-burning substances, which generate relatively low pressures. Gunpowder is a low explosive. Dynamite and ANFO (ammonium nitrate and fuel oil) are high explosives. They need a detonator to trigger them off.



BASIC LAWS OF COMBINATION

Most chemical elements undergo chemical reaction with other elements to form a wide variety of compounds. Although the precise nature of the changes taking place each time varies from reaction to reaction, certain basic laws apply to every reaction.

One is the *conservation of mass*. This simply states that no matter is lost or gained overall as a result of a chemical reaction. When 16 grams of methane burn, they combine with 64 grams of oxygen from the air to form 44 grams of carbon dioxide and 36 grams of water: $16 + 64 = 44 + 36 = 80$.

Another is the *law of constant composition*. A given chemical compound always contains the same elements in the same fixed proportions by mass. Lead monoxide can be prepared in several ways—by heating lead in air, or by decomposing lead carbonate or lead nitrate. In both cases the lead monoxide formed will always contain 7.7 grams of oxygen to every 100 grams of lead.

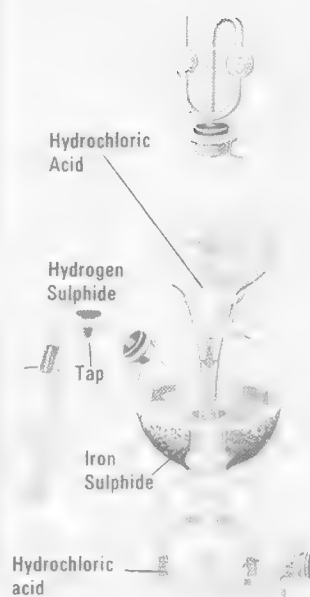
A third is the *law of multiple proportions*, which applies when two elements combine together to form more than one chemical compound. When this happens, the law states that the varying masses of one element which combine with a given mass of the other are in simple proportion. Take for example the oxides of nitrogen. A hundred grams of nitrogen will combine with the following masses of oxygen: in the pentoxide, 285 g; in the dioxide, 228 g; in the trioxide, 171 g; in nitrogen oxide, 114 g; and in dinitrogen (nitrous) oxide, 57 g. Dividing by 57, the amounts of oxygen combined in the various oxides are in the ratios 5:4:3:2:1.

These laws are consistent with the atomic

theory, first advanced by Dalton in 1803. Dalton suggested that the chemical elements are made up of tiny atoms which cannot be subdivided during a chemical change. Each element has a different kind of atom with a different mass and different properties. Chemical compounds are formed by the union of different atoms in simple proportions.

Five years after Dalton had advanced his atomic theory, Gay-Lussac observed that gases react in simple proportion by volume. When gases react together, their volumes and those of their gaseous products bear a simple ratio to one another, provided that the volumes are measured at the same temperature and pressure. For example, one volume of hydrogen and one volume of chlorine react to give two volumes of hydrogen chloride. Two volumes of hydrogen and one volume of oxygen react to form two volumes of steam.

Since substances react in simple proportions by atoms (Dalton) and gases react in simple proportion by volume (Gay-Lussac), there is obviously a relationship between the number of atoms present in equal volumes of gases under similar conditions. Avogadro put forward a solution to the problem. He suggested that the physical unit of a gas is not a single atom but a group of two or more atoms called a *molecule*. And he advanced a hypothesis which accounted for Gay-Lussac's observations: equal volumes of all gases under the same conditions of temperature and pressure contain the same number of molecules. The actual number of molecules in the gram-molecular weight (molecular weight in grams) of any substance is 6.02×10^{23} . This figure is called the Avogadro constant.



Above: Kipp's apparatus, or generator, for the continuous production of such gases as hydrogen, hydrogen sulphide or carbon dioxide. Hydrogen sulphide, for example, is produced when hydrochloric acid from the bottom vessel enters the middle bulb, which contains iron sulphide. This happens when the tap is opened. When the tap is closed, pressure builds up in the middle bulb and forces the acid back into the base and thence into the upper bulb.

pletely would require a temperature of some 800°C. But, with the addition of a small quantity of manganese dioxide as a catalyst, decomposition proceeds more readily at a much lower temperature. At the end of the reaction, it is found that the manganese dioxide is unchanged chemically. This ability to remain unchanged is typical of all catalysts.

Among the many materials that have catalytic properties platinum and the metals related to it are the most important. Platinum is used, for example, as a catalyst in the manufacture of sulphuric acid and in the cracking of petroleum hydrocarbons. Transition metals such as iron and nickel are also useful catalysts. Iron is used to catalyse the Haber synthesis of ammonia from nitrogen and hydrogen.

Reversible Reactions and Equilibrium

This reaction differs from most of the previous examples because it is a reversible reaction. The reagents react to form ammonia, but at the same time the ammonia tends to decompose into its constituent elements. We write such a reversible reaction as:



After a while the reaction will reach equilibrium, with the rates of formation and decomposition the same. At this point there will be a mixture of nitrogen, hydrogen and ammonia.

To obtain the highest yield of ammonia the equilibrium must be displaced as far to the

right as possible. We can improve the yield of ammonia by increasing the pressure of the system (to about 1000 atmospheres). This is explained by *Le Chatelier's principle*, which states that when there is a change in the external conditions affecting a reversible reaction, the reaction will adjust itself to nullify the change. The reaction is:

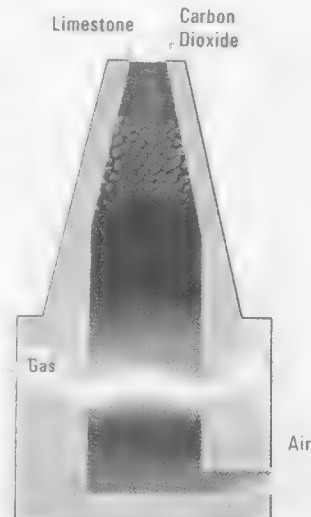


One volume of nitrogen combines with 3 volumes of hydrogen to form 2 volumes of ammonia. When you increase the pressure on the system, the system adjusts itself to counteract the pressure increase. This can happen if more product is formed, for the product occupies only half the volume as that occupied by the reagents.

Increasing the reaction temperature, however, shifts the equilibrium to the left. The reaction is exothermic, and less product tends to form to counteract an external temperature increase. However, at low temperatures, the rate of reaction is too low to be economic. Therefore the temperature is increased (to about 500°C), despite the adverse effect this has on the yield of ammonia.

The presence of the catalyst, incidentally, has no effect on the position of equilibrium, for it accelerates the forward and reverse reactions to the same extent. Using a catalyst in a reversible reaction simply enables the position of equilibrium to be attained more rapidly.

Below: The thermal decomposition of limestone (calcium carbonate) into lime (calcium oxide) and carbon dioxide is an example of a reversible reaction. If the carbon dioxide were allowed to remain in contact with the lime, it would tend to recombine with it.





Electrochemistry

There are basically two kinds of substances that will conduct electricity. First there are metals, in which the electrons are free to flow under a potential difference, or voltage. The flow of electrons constitutes an electric current. Certain non-metals, notably carbon, also conduct electricity.

Electrolytes are the second kind; they conduct electricity in solution and in the fused (molten) state. They are substances such as acids, bases, and salts which form charged atoms, or *ions*, when they dissolve in water. Conduction of electricity is brought about by the migration of these ions through the solution.

The two conductive processes—in metals and electrolytes—differ in one respect. When electric current is passed through a metal, no chemical change takes place (although physical changes, for example heating, may occur). When electric current is passed through an electrolyte, however, the electrolyte decomposes. The process of decomposing an electrolyte by an electric current is *electrolysis*.

Electrolysis plays an important part in chemistry and industry. It is used, for example, in the extraction and refining of metals and in the preparation of other chemicals. Aluminium is prepared by the electrolysis of alumina (aluminium oxide) dissolved in molten cryolite (see page 188). Pure copper is refined

Above: The anode blocks of an aluminium cell. Aluminium is produced by the electrolytic decomposition of alumina (aluminium oxide) dissolved in molten cryolite (sodium aluminium fluoride). It is the only economic way of producing the metal from its ores. Many other metals are produced from their compounds by means of electrolysis, including sodium, potassium, and magnesium.

from crude copper by electrolysis in copper sulphate solution. The electrolysis of brine (sodium chloride solution) is the main method of producing chlorine and sodium hydroxide (caustic soda). Electrolysis is also the basis of *electroplating*.

Electrolysis is essentially a process in which electrical energy is converted into chemical energy. The reverse can also occur, with chemical energy being converted into electrical energy. This is what happens in an electric cell or battery. In the lead-acid storage battery, or accumulator, both processes take place in succession. Electrolysis occurs while the battery is being charged. The reverse process occurs on discharge, and electric current is produced.

In a simple electrolytic cell, electricity from an external source—say, a battery—is carried into and out of the electrolyte solution by metal plates, or *electrodes*. The electrode connected to the positive pole of the battery is called the *anode*, and that connected to the negative pole, the *cathode*. When current is flowing, the cathode acquires an excess of electrons and becomes negatively charged, while the anode gives up electrons to the battery and becomes positively charged.

Mechanism of Electrolysis

Strong acids, strong bases, and their salts are known as strong electrolytes because they are almost completely split up, or *dissociated*, into ions in solution. The salt sodium chloride, for example, is almost completely ionic, even in crystal form. In chemical combinations the sodium atom readily loses an electron to become a positive ion. Similarly, chlorine readily gains an electron to become a negative ion. In any salt crystal the ions are fixed in a geometrical pattern and are held together by attraction between the opposite charges. When the salt is dissolved in water, the mutual attraction is reduced, and the ions are free to move. The same holds if the salt is melted. When electricity is applied to electrodes in the electrolyte, the ions migrate to the electrodes under electrical attraction. The positive ions migrate to the cathode (negative electrode), while the negative ions migrate to the anode (positive electrode).

In the electrolysis of molten sodium chloride positive sodium ions (Na^+) migrate to the cathode, and negative chlorine ions (Cl^-) migrate to the anode. When a Na^+ ion touches the cathode, it receives an electron and

THE LAWS OF ELECTROLYSIS

1. Chemical decomposition of the electrolyte during electrolysis takes place only at the surface of the electrodes.
2. The mass of substance liberated during electrolysis is proportional to the strength of the current and to the time for which it passes—in other words, to the quantities of electricity which passes through the electrolyte.
3. The quantity of electricity required to deposit one mole of a metal is in simple proportion to that required to deposit one mole of silver.

becomes converted to a sodium atom. And metallic sodium forms. When a Cl^- ion reaches the anode, it gives up an electron to become chlorine gas, which is given off (see page 206). During electrolysis, then, electrons are simultaneously passing into and leaving the electrolyte, effectively constituting an electric current.

Another typical example of electrolysis is that of copper sulphate solution with copper electrodes. In the solution copper sulphate is completely ionized into positive copper ions (Cu^{2+}) and negative sulphate ions (SO_4^{2-}). In addition the water itself is slightly ionized into hydrogen ions (H^+) and hydroxyl ions (OH^-). The copper and hydrogen ions migrate to the cathode. But copper alone is discharged because it has a greater tendency to accept electrons and become an atom than hydrogen. So metallic copper is deposited on the cathode. The sulphate and hydroxyl ions migrate to the anode. They are not discharged because they have less tendency to lose electrons than the copper in the anode. So the copper in the anode loses two electrons instead and passes into solution as Cu^{2+} . The net result of the electrolysis, therefore, is that the copper anode dissolves, while copper is deposited on the cathode.

This form of electrolysis is utilized in copper refining. A pure copper plate is used as the cathode, while crude copper is used as the anode. During electrolysis the anode dissolves, while pure copper is deposited on the cathode. The impurities remain in solution or collect as a slime beneath the anode.

Electroplating

Electrodeposition of a metal by electrolysis also forms the basis of electroplating. The idea of electroplating is usually to give an attractive, long-lasting finish to a relatively unattractive or corrosion-prone metal. Mild steel, for example, is coated first with copper, then with nickel, and finally with chromium. This is collectively called *chromium plating*. The copper coating forms a good key for the nickel layer, which provides the main corrosion protection. The chromium layer is also corrosion-resistant, but, more important, it imparts great hardness and durability. The layers are very thin indeed: the nickel is often less than 0.025 millimetre thick, while the chromium can be 100 times thinner still.

In electroplating copper on to steel, copper sulphate solution cannot be used because it is corrosive. A cyanide solution is used instead. Cyanide solutions are also used for electroplating with gold and silver. Silver plating is practised on a very large scale, plated articles being only a fraction of the cost of the solid silver equivalent. In nickel plating a pure nickel anode and an acidic solution of nickel salts are used. Chromium is plated from a solution of chromic acid, with an insoluble lead anode; to increase plating efficiency sulphate and complex fluoride ions are incorporated in the electrolyte to act as catalysts.

ELECTROCHEMICAL SERIES

When a metal is placed in a solution of its ions, a potential difference, or voltage, exists between the metal and the solution. It is called the *electrode potential* of that metal. The standard, or molar, electrode potential is that which exists when the solution is molar. (A molar solution of a substance is one which contains in each litre a mass in grams of the substance equal to its molecular weight.)

Molar electrode potentials are measured on a scale which takes the molar electrode potential of hydrogen to be zero. Those of common metals are as follows:

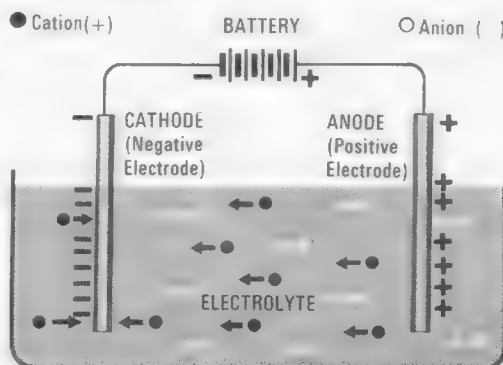
Electrode	Electrode Potential	Electrode	Electrode Potential
K/K ⁺	-2.92	Sn/Sn ²⁺	-0.14
Na/Na ⁺	-2.71	Pb/Pb ²⁺	-0.13
Mg/Mg ²⁺	-2.37	Pt(H ₂)/H ⁺	0.00
Al/Al ³⁺	-1.66	Cu/Cu ²⁺	-0.34
Zn/Zn ²⁺	-0.76	Hg/Hg ²⁺	+0.79
Fe/Fe ²⁺	-0.44	Ag/Ag ⁺	+0.80
Cd/Cd ²⁺	-0.40	Au/Au ³⁺	+1.50

This sequence of metals is known as the *electrochemical series*. It provides a useful means of classifying metals and predicting how a metal will behave under certain conditions; it also provides a basis for electric-cell voltage calculations.

Metals at the head of the series with high negative electrode potentials readily lose electrons to become ions; conversely, their ions do not readily take up electrons to yield atoms. Such metals are said to be *electropositive* since they readily yield electropositive ions. The hydroxides of strongly electropositive metals are strongly alkaline, and are not hydrolysed (decomposed by water) in solution. Weakly electropositive metals—those near the end of the electrochemical series—form weakly basic hydroxides, and their salts tend to hydrolyse in solution.

A more electropositive metal will displace a less electropositive metal from its salts. Metallic iron, for example, will precipitate copper from a solution of copper sulphate. The iron has a greater tendency to form ions than copper has, and will lose electrons to do so; these electrons are transferred to the copper ions, which form atoms that are precipitated. Metals above hydrogen in the electrochemical series will displace hydrogen from an acid solution because they form ions more readily than hydrogen does. (In other words, acid attacks the metal, liberating hydrogen.) The position of copper below hydrogen in the electrochemical series explains why copper rather than hydrogen is discharged at the cathode. The hydrogen has a greater tendency to remain in solution as ions than copper does, so copper is discharged.

Aluminium owes its corrosion resistance to the presence of an adherent surface film of oxide. The thickness of this film can be increased by electrolytic means to improve corrosion resistance still further. The process is called *anodizing* (see page 189). The freshly anodized surface can be impregnated with pigments to produce a colour-anodized film. This cross-section of an anodized film ($\times 800,000$) shows the pigment (in this case a cobalt salt) as dark strips.

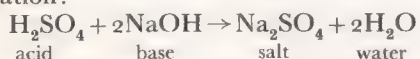


Principles of the process of electrolysis. The electrolyte is split up into positively charged ions, or cations, and negatively charged ions, or anions. When current is passed through the electrolyte via the anode (positive electrode) and cathode (negative electrode), the cations migrate to the cathode, while the anions migrate to the anode.

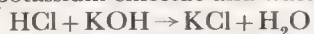


Acids, Bases and Salts

One of the simplest of chemical reactions is that between an acid and a base to yield a salt plus water. When sulphuric acid (H_2SO_4) and the base sodium hydroxide (NaOH) react, they form the salt sodium sulphate and water. We can represent the reaction by the equation:



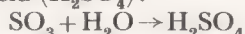
Similarly, hydrochloric acid (HCl) reacts with potassium hydroxide (KOH) to form the salt potassium chloride and water:



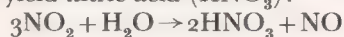
Sulphuric acid and hydrochloric acid are typical acids. They contain hydrogen and will exchange hydrogen for sodium when treated with sodium hydroxide solution. Sodium sulphate and potassium chloride are typical salts. They are compounds formed by the replacement of hydrogen in an acid by a metal. Sodium and potassium hydroxides are typical bases. They react with acids to yield a salt and water only.

Acids

Sulphuric acid is not only the most widely used of all acids, it is also the most important industrial chemical. About 80 million tonnes are produced every year. Much of this is used for the manufacture of superphosphate and other fertilizers and for pickling steel. Sulphuric acid is made by oxidizing sulphur into its oxide sulphur dioxide (SO_2), and then oxidizing this oxide into sulphur trioxide (SO_3). Sulphur trioxide reacts with water to produce sulphuric acid (H_2SO_4):



Sulphur trioxide is the anhydride of sulphuric acid. It is an example of an acidic oxide, which forms an acid when it combines with water. In general, the oxides of non-metals (like sulphur) are acidic. Those of chlorine, nitrogen, and phosphorus, for example, all yield acids by reaction with water. Nitrogen dioxide (NO_2) reacts with water in the following way to yield nitric acid (HNO_3):



Above: Continuous filaments of viscose rayon emerging from the acid bath following the 'spinning' operation. In rayon manufacture wood-pulp is treated with caustic soda to form alkali cellulose. After a period of aging, crumbs of alkali cellulose are treated with carbon disulphide to form cellulose xanthate, which in turn is treated with dilute caustic soda solution. The thick orange-brown sodium cellulose xanthate that forms is allowed to ripen and, after repeated filtering, is forced through the tiny holes of a spinneret. The emergent filaments encounter the acid bath, whereupon they change back into pure cellulose. That is why rayon is called a regenerated fibre.

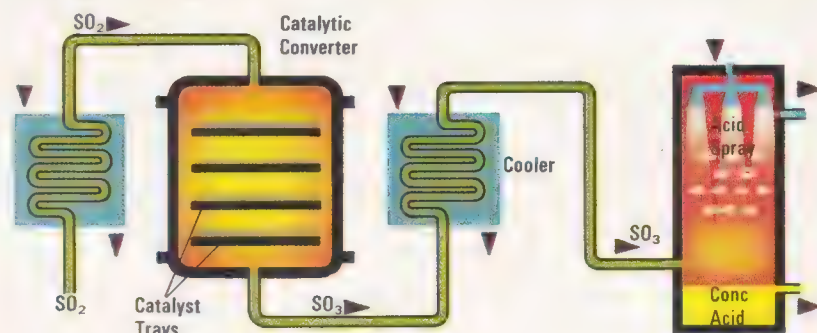
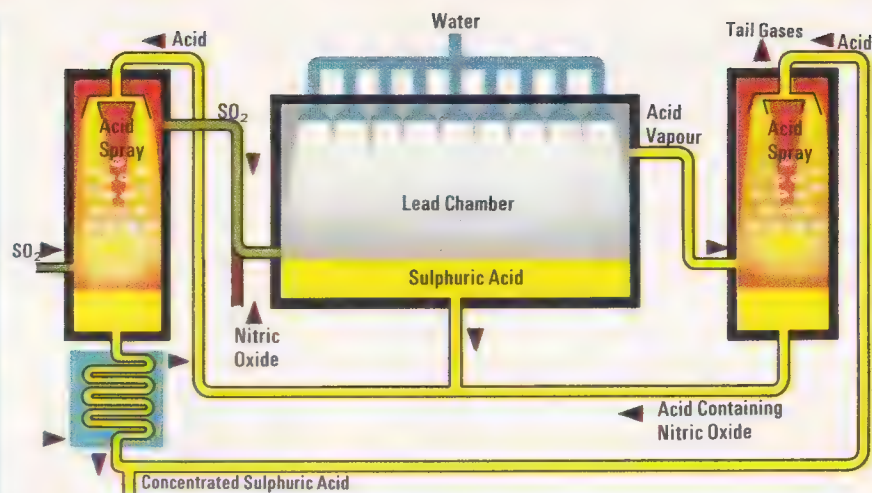
SULPHURIC ACID

Sulphuric acid, often called *oil of vitriol*, is a dense oily liquid, which is a strong acid, a powerful oxidizing agent, and a vigorous dehydrating agent. It combines violently with water, and if only a few drops of water are added to the concentrated acid the reaction is explosive. Sulphur trioxide will dissolve in the concentrated acid to form fuming sulphuric acid, or *oleum*. Oleum is often used in the preparation of organic chemicals.

Two main methods are employed to produce sulphuric acid — the *chamber* and the *contact* processes, the latter being by far the most important. The chamber, or lead-chamber process is so called because acid formation takes place in large chambers of sheet lead. The essential reaction is the oxidation of sulphur dioxide (SO_2) in moist air, in the presence of oxides of nitrogen. The diagram on the top right shows the lead-chamber set-up. The tail gases contain nitrogen oxides, which are recovered and recirculated.

The diagram on the lower right outlines the contact process for sulphuric-acid manufacture. A mixture of sulphur dioxide and air is passed over a heated catalyst, whereupon the sulphur dioxide is converted to sulphur trioxide, which is led into a dilute acid spray. It reacts with the water present to form more acid, and concentrated acid collects at the foot of the tower. The catalyst for the contact process is usually platinum, finely divided in asbestos (platinized asbestos), or vanadium pentoxide.

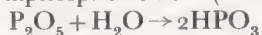
The sulphur dioxide may be obtained in a variety of ways, depending on the cheapest material available to the acid-making plant. Occasionally elemental sulphur is burned in air. Often iron pyrites — iron sulphide — is roasted in air, whereupon sulphur dioxide forms.



Above: Two methods of manufacturing sulphuric acid — the lead-chamber process (top) and the contact process (bottom). Most acid is today made by the contact process.

Below: Automatic titration apparatus like this is now being increasingly used in industrial chemical laboratories to carry out routine titrations. The pH meter measures hydrogen-ion concentration.

Phosphorus(V) oxide, P_2O_5 , reacts with water to form metaphosphoric acid (HPO_3):

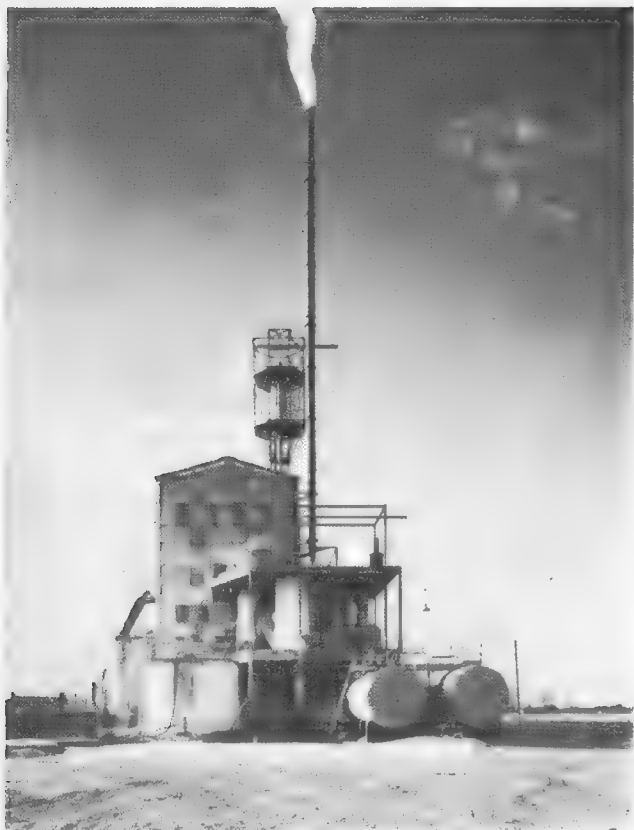


It is the anhydride of metaphosphoric acid. When metaphosphoric acid is boiled, it is converted to orthophosphoric acid, H_3PO_4 . In all phosphorus gives rise to no fewer than eight more acids: H_3PO_2 , H_3PO_3 , $\text{H}_4\text{P}_2\text{O}_6$, $\text{H}_4\text{P}_2\text{O}_5$, $\text{H}_4\text{P}_2\text{O}_7$, HPO_2 , H_3PO_5 , and $\text{H}_2\text{P}_2\text{O}_3$.

Nitric, sulphuric, and orthophosphoric acids differ in the number of hydrogen atoms they contain. Nitric acid has one, and is termed *monobasic*. It forms only one series of salts — the nitrates, as in sodium nitrate (NaNO_3). Sulphuric acid has two, and is termed *dibasic*. It can form two series of salts — the bisulphates, or hydrogen sulphates, as in sodium hydrogen sulphate (NaHSO_4); and the sulphates, as in sodium sulphate (Na_2SO_4). Orthophosphoric acid has three hydrogen atoms; it is *tribasic*. It can form three series of salts: dihydrogen phosphates (as in NaH_2PO_4), hydrogen phosphates (as in Na_2HPO_4), and orthophosphates (as in Na_3PO_4).

In water an acid *dissociates*, or splits up, to give ions: the hydrogen part loses an electron and forms positively charged hydrogen ions (H^+). The other part — the acid radical — gains an electron to form negatively charged ions. The presence of the hydrogen ions confers acidity on the solution, and an acid is



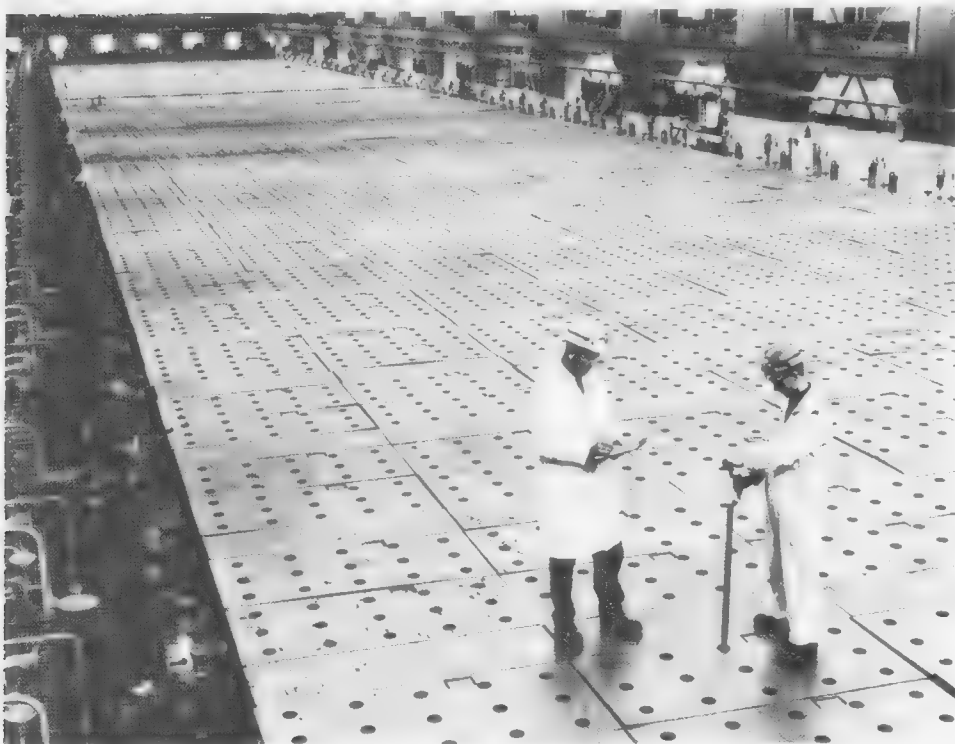


A phosphoric acid plant. Phosphoric acid is widely used for the production of fertilizers such as superphosphate. It is also a major ingredient of anti-rust compounds, reacting with rust (iron oxide) to form an adherent phosphate film.

judged to be strong or weak according to its ability to yield hydrogen ions in solution.

Hydrochloric, nitric and sulphuric acids (the so-called mineral acids) are for the most part dissociated in solution and yield a high concentration of hydrogen ions. They are therefore deemed strong acids. Acetic acid, on the other hand, is a weak acid which will yield relatively few ions in solution. And carbonic acid, which is very weak indeed, will yield scarcely any. Carbonic acid, H_2CO_3 , is formed by bubbling carbon dioxide—an acidic oxide—through water. It is dibasic and

Most caustic soda these days is produced by the electrolysis of brine (sodium chloride). Chlorine is produced at the same time. The picture below shows the chlorine cell room.



HYDROGEN-ION CONCENTRATION

The degree of acidity of a solution depends upon the number of hydrogen ions present. In a *molar solution* of a monobasic acid, the concentration of hydrogen ions is 1 gram-ion per litre. (In chemistry, a molar solution of a substance is one which has a concentration of one mole (the molecular weight in grams) per litre.) The other extreme of acidity is represented by a molar solution of a monoacidic base. The hydrogen-ion concentration in such a solution is about 1×10^{-14} gram-ion per litre.

The hydrogen-ion concentration of a solution can thus be anywhere between these two extremes: 1 and 1×10^{-14} . The range is so wide that it is convenient to express hydrogen-ion concentration on a logarithmic scale in terms of *pH*. *pH* is the logarithm to the base 10 of the hydrogen-ion concentration, with the negative sign omitted. The range of acidity, from $10^0 (= 1)$ to 10^{-14} , is represented by *pH* values from 0 to 14. An example of an intermediate value is as follows: If the hydrogen-ion concentration (*h*) is 0.051 gram-ion per litre, $\log h = 2.700 = -1.300$. Therefore *pH* = 1.300.

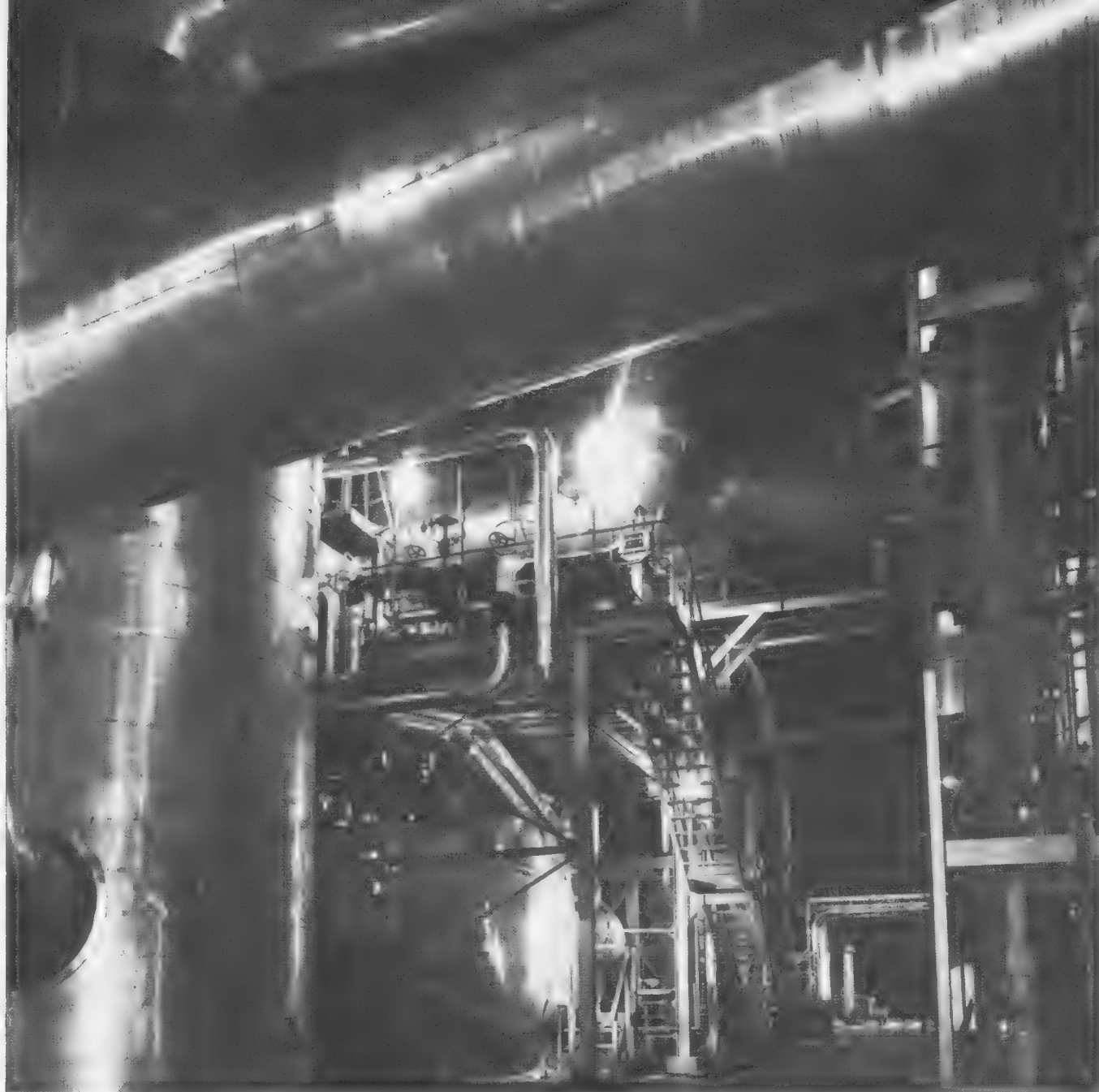
The hydrogen-ion concentration in pure water is 10^{-7} gram-ion per litre. Water is split up equally into hydrogen ions (H^+) and hydroxyl ions (OH^-). ($\text{H}_2\text{O} \rightleftharpoons \text{H}^+ + \text{OH}^-$) So the hydroxyl-ion concentration in pure water is also 10^{-7} . Since pure water is neither acidic nor alkaline, a hydrogen-ion concentration of 10^{-7} (that is, *pH* = 7) is regarded as a neutral solution. A solution in which the hydrogen-ion concentration is greater than 10^{-7} (that is, *pH* less than 7) is acidic. A solution with a hydrogen-ion concentration of less than 10^{-7} , or a hydroxyl-ion concentration greater than 10^{-7} (*pH* greater than 7), is alkaline.

The process of bringing a solution to the neutral point, at *pH* = 7, is called *neutralization*. This is usually done by adding an alkali to an acidic solution, or an acid to an alkaline solution. If added in suitable amounts, the two react to form a salt plus water, there being no surplus hydrogen or hydroxyl ions present save those from the water (*pH* = 7). Neutralization forms an essential part of volumetric analysis in analytical chemistry (see page 184). Substances called *indicators* are used to determine the neutral point. These are weak acids and weak alkalis which are colour sensitive to the hydrogen-ion concentration. A change in their colour indicates the neutral point (see page 184).

forms two kinds of salts, the hydrogen carbonates (as in bicarbonate of soda, NaHCO_3) and the carbonates (as in washing soda, Na_2CO_3).

Acids have a sour taste, not that tasting strong acids is advisable! But we are familiar with the sour taste of the weak organic acids, such as the acetic acid in vinegar and the citric acid in lemon juice. The stronger acids, such as sulphuric, will attack zinc and many metals, and hydrogen will be given off. Most acids will dissolve carbonates and hydrogen carbonates, and carbon dioxide will be given off. The solution used to remove chalk deposits (fur) in kettles contains formic acid.

You can test for an acid with a piece of blue litmus paper. If acid is present, the blue paper will turn red. Litmus is one of several substances called *indicators* whose colour is different in acidic and basic solutions.



Bases

Sodium and potassium hydroxides are almost completely dissociated in solution into positive metal ions (Na^+ , K^+) and negative hydroxyl ions (OH^-). They are able to react with and neutralize strong acids, and are classed as strong bases. Some bases are much weaker and yield fewer hydroxyl ions in solution. Ammonium hydroxide, which exists only in solution, is an example. Calcium hydroxide, or slaked lime, is another weak base.

Sodium and potassium hydroxides are better known as caustic soda and caustic potash. Both will burn the flesh if touched. They are widely used in industry as reagents in chemical processing and in the manufacture of soaps, rayon, and paper. Ammonium hydroxide is, like caustic soda, a widely used household cleansing agent. Because of its cheapness calcium hydroxide is used in preference to other bases in industry to neutralize acids. Farmers use the solid form, slaked lime, to neutralize acid soils.

These four soluble hydroxides are called *alkalis*. They are the most important and

best-known of the bases. The other bases are the oxides, and (insoluble) hydroxides of metals. They are classed as bases because they neutralize acids to produce a salt and water only. Alkalis are usually the result of the reaction of a metal oxide with water. Sodium and calcium hydroxides, for example, result from the reactions of sodium oxide (Na_2O) and calcium oxide (CaO) respectively with water, as in:



Not all metal oxides, however, are wholly basic in character. Some can be acidic in certain circumstances. In the presence of acids these so-called *amphoteric* oxides act as bases, and in the presence of alkalis they act as acids. Aluminium, zinc and tin are among the metals that form amphoteric oxides. Alumina (Al_2O_3), for example, acts acidically when it reacts with sodium hydroxide, forming a salt, sodium aluminate (NaAlO_2), and water:



It reacts with acids to form a salt and water, as in:



The sulphur burner in a sulphuric-acid manufacturing plant. Sulphuric acid is the most important industrial chemical and is often called the 'lifeblood' of industry. Over 80 million tonnes of the acid are produced in the world every year.



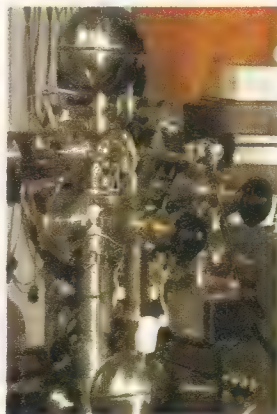
Chemists at Work

Chemistry is the study of the make-up and properties of substances and the changes they undergo. It emerged as an organized scientific discipline in the mid-1800s, when systematic methods of analysing, evaluating and classifying chemical substances were becoming established. The growth in knowledge led to the development of new chemical processes, the discovery of new materials, such as coal-tar dyes and man-made plastics, and the birth of a large-scale chemical industry.

As chemical knowledge expanded, several branches of chemistry emerged. Today chemists may specialize in inorganic or organic chemistry, biochemistry, physical and analytical chemistry, or with the practical application of chemistry—chemical engineering.

Inorganic chemistry includes study of the chemical elements and the compounds they form, excluding those of carbon. Organic chemistry is the study of the carbon com-

Above: A familiar chemical laboratory scene, which has not changed greatly over the years. But increasingly in research laboratories such sophisticated apparatus as mass spectrometers (below) are being used for analysis.



pounds; it is so-called because such compounds are found in or derived from living organisms. Biochemistry is concerned with the chemical processes that take place in living things. Physical and analytical chemistry are concerned with the separation and identification of chemical substances and the evaluation of their properties and reactions. Its methods are applicable to inorganic and organic chemistry alike. The text that follows describes many of the important techniques chemists use.

Separation Techniques

In chemical analysis it is often necessary to separate substances from one another in order to identify them. There are very few tests that are specific to a single substance, and confusion can arise if too many substances in a mixture react at the same time. For certain mixtures physical separation of the substances can be effected by *filtration*, *distillation*, *sedimentation*, and *centrifuging*. But these techniques are effective only if the substances in the mixture have appreciably different particle size, density, boiling point, solubility, or whatever. Separation by *precipitation* is sometimes possible, a chemical reagent being added to cause

a precipitate to form. Progressive separation by precipitation forms the basis of the classical method of identifying metals in qualitative analysis (see below).

Among the modern methods of separation *chromatography* is most successful. It is capable of yielding quick results, and of separating mixtures containing a large number of similar components. The Russian botanist Mikhail Tsvett first used the word chromatography ('colour-writing') in 1906, applying it to a method he devised of separating complex mixtures of plant pigments. He washed a solution containing the pigments through a column packed with powdered chalk, and found that the coloured pigments migrated to different parts of the column.

Modern methods of chromatography do not always involve colour separation, but they all work on the same basic principle. The sample mixture to be separated is dissolved in a solvent absorbed by a supporting substance, or *stationary phase*. Another solvent, the *mobile phase*, is then passed through the stationary phase. Components in the sample separate out because of their different rates of migration through the stationary phase in the wake of the mobile phase.

Three basic types of chromatography are in use—paper, column, and gas chromatography. In paper chromatography the stationary phase is a strip of porous paper. A drop of the sample to be analysed is placed on the paper, the end of which is dipped into a suitable solvent that acts as the mobile phase. As the solvent is absorbed by the paper, it travels through the sample, and the components in the sample separate. In column chromatography a long, narrow cylindrical column is packed with a suitable absorptive material, such as charcoal, alumina, or silica gel. This column packing (or a liquid that wets the packing) acts as the stationary phase.

Gas chromatography is the most sensitive and versatile of the methods. It is very much faster than the others, separation being effected in a matter of seconds or minutes. Gas chromatography also uses a packed column, which is usually mounted horizontally and may be coiled. The stationary phase is often a liquid such as glycerine or silicone oil. The column is usually heated by a vapour jacket to accelerate component separation. An inert gas such as nitrogen or helium flows steadily through the tube, acting as the mobile phase. A minute amount of sample is injected into the column and immediately vaporizes. Its components separate out as it passes through the column and emerge at the far end in succession. Their presence is detected by changes in the thermal conductivity of the gas stream, or by other signs, and is recorded as a moving chart. Often the components can be identified by the length of time they take to pass through the column under a given gas flow. If this is not possible, the components can be collected and analysed by other sensitive techniques, such as mass spectroscopy

(see page 185), which can identify substances present in minute concentrations.

Qualitative and Quantitative Analysis

The classical methods of analysing and identifying chemical substances have been largely superseded in modern chemical research laboratories by high-speed micro techniques which rely on sophisticated instruments. The classical methods are nevertheless an invaluable aid to the understanding of fundamental chemical principles. Qualitative analysis aims to establish the nature of a chemical substance, while quantitative analysis aims to measure the amount of the substance.

In qualitative analysis, certain spot tests may quickly reveal the identity of a simple substance. Among these tests are the flame test, borax-bead test, and charcoal-block test. In the flame test a little of the substance is held in a bunsen flame on the end of a clean platinum wire. Certain metal salts colour the flame vividly, including sodium (orange), strontium (crimson), and barium (green). In the borax-bead test a little borax is heated on a platinum wire, whereupon it swells up and then fuses into a clear glass bead. If the bead becomes coloured when it is dipped in the unknown substance and heated, the metal in the substance can be identified. A blue colour, for example, indicates cobalt. In the charcoal-block test a sample of the substance is placed on a charcoal block and heated fiercely. If lead, copper, tin, zinc, or iron ions are present, they will be reduced by the carbon to metal.

Often these tests form part of a more systematic analysis which is necessary when a complex mixture of inorganic substances is encountered. These substances will in general be compounds of a metallic element with simple non-metallic elements such as sulphur or oxygen, or with acid radicals such as sulphate ($-\text{SO}_4$) or chloride ($-\text{Cl}$). Preliminary tests may be carried out on the mixture while it is in a dry state. It may, for instance, be heated to see if any charring occurs (indicating carbon), or if any water is given off, or if any other decomposition occurs. But the main tests take place in solution, when the task is to identify metal cations (positive ions, Fe^{2+} , Na^+ , Ca^{2+}) and anions (negative ions, Cl^- , SO_4^{2-} , NO_3^-). Identifying anions can often be a problem, but the identification of cations can be carried out systematically. A common scheme is given below. It consists of a repetitive cycle of adding one reagent, filtering any precipitate that forms, and treating the filtrate with another reagent.

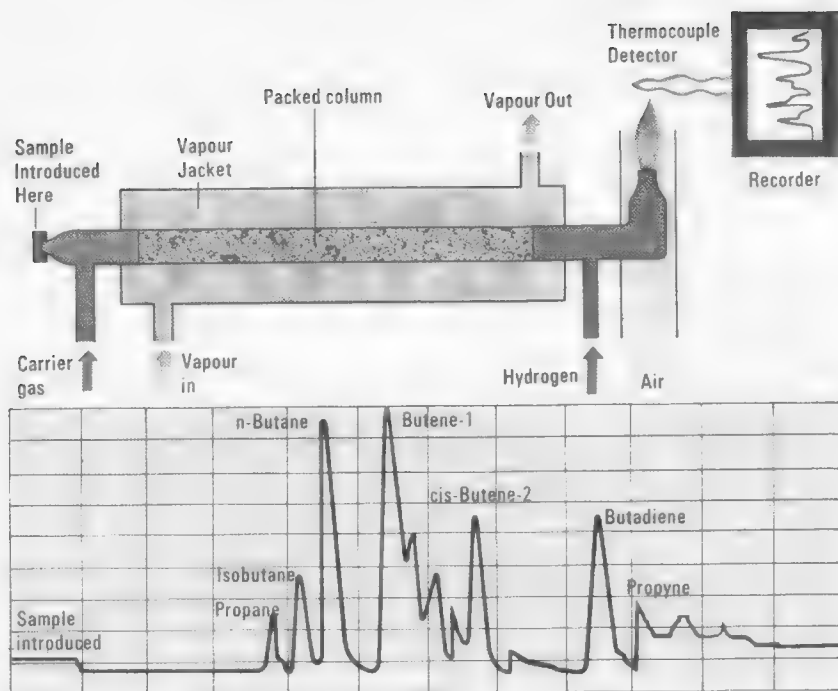
To a solution of the unknown mixture, hydrochloric acid (HCl) or ammonium chloride (NH_4Cl) is added. If any of the metals lead, silver, or mercury(I) (Hg^+) are present, they will be precipitated as chlorides: PbCl_2 , AgCl , and Hg_2Cl_2 . Hydrogen sulphide (H_2S) gas is then bubbled through the filtrate. A precipitate will indicate the presence of metal sulphides—of copper, cadmium, mercury(II) (Hg^{2+}), tin, lead, arsenic, antimony,



Above: Examples of paper chromatography, showing the colour separation of components.

Below: The characteristic colours displayed by compounds of the alkali and alkaline-earth metals when thrust into a Bunsen flame during the flame test.

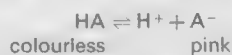




INDICATORS

The indicators used in acid-base titrations indicate when the neutralization point has been reached by changing colour. Litmus is red in acid solution and blue in alkaline solution, for example. We can explain the colour change in the following way.

Indicators are weak acids and weak bases which are only slightly dissociated, or split up into ions, in solution. Consider the common indicator phenolphthalein, which is a weak organic acid. We can represent it as HA, which dissociates and establishes an equilibrium thus:



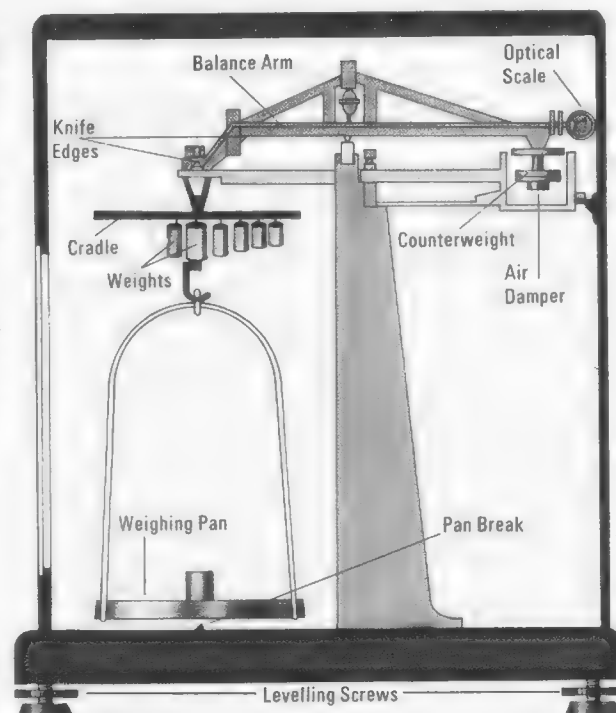
The undissociated acid (HA) and the hydrogen ion (H^+) are colourless, but the negative ion (A^-) is pink. When the indicator is added to an acidic solution, the mass action of the hydrogen ions present in the solution will upset the equilibrium and cause the dissociation to go into reverse (from right to left in the equation). Hence scarcely any A^- ions will form, and the indicator will be colourless.

Consider now what happens when the indicator is added to an alkaline solution. This solution contains hydroxyl ions (OH^-), which combine with the hydrogen ions from the indicator to form water. To make good the loss, more indicator ionizes, supplying, of course, more and more negative ions, which are coloured. Hence, the indicator will appear coloured.

Each indicator changes colour at different hydrogen-ion concentrations, or pH values (see page 180). The selection of a suitable indicator depends on the type of neutralization being carried out. With a strong acid and a strong base a colour change near the neutral point ($\text{pH} = 7$) is called for, so litmus is satisfactory. With a strong acid and a weak base, an indicator changing on the acid side of neutral is required, such as methyl red or methyl orange ($\text{pH} < 7$). The solution of a salt of a strong acid and a weak base is acidic because of hydrolysis. Conversely, the solution of a salt of a weak acid and a strong base is alkaline. A suitable indicator for a weak-acid/strong-base titration would be phenolphthalein, which changes on the alkaline side ($\text{pH} > 7$).

Top: Diagram of a simple gas-chromatography set-up. Inert gas carries the vaporized sample through the column. Its constituents separate out as they come into contact with the absorptive stationary phase on the packing. Eventually they emerge in turn from the column, where their presence is detected and recorded as a trace similar to that shown above. The constituents can often be identified by the time they take to pass through the column. The height of the peaks is an indication of how much of the constituent is present.

A modern single-pan balance, now widely used in chemical laboratories. It is a constant-weight type. With nothing in the pan, the weight of the weights and the pan just balances the counterweight. The sample to be weighed is placed on the pan, and weights are lifted mechanically from the cradle until the beam is in balance again. The weight of the sample is thus measured by the sum of the weights removed from the cradle. This contrasts with the traditional two-pan balance in which weights are added to one pan to balance the weight of the sample in the other.



or bismuth. The acidic solution remaining is then neutralized with ammonia solution (NH_4OH). If aluminium, chromium or iron are present, they will be precipitated as hydroxides, which can be distinguished by their colour—aluminium white, chromium greenish, and iron brown.

Hydrogen sulphide is then bubbled through the now alkaline filtrate, causing any manganese, cobalt, nickel and zinc to be precipitated as sulphides. Cobalt sulphide and nickel sulphide are black, manganese sulphide brownish-white, and zinc sulphide white. The filtrate is then evaporated, and ammonia solution and ammonium carbonate are added to the remaining solid. A precipitate will indicate the presence of carbonates of the alkaline-earth metals—calcium, strontium and barium. These can be distinguished by a flame test. The only ions remaining in solution will be sodium, potassium, or magnesium.

In quantitative analysis two main methods are used, the *gravimetric* and the *titimetric*. The first involves weighing, the second titrating. In gravimetric analysis the composition of a mixture is obtained by separating each component, perhaps as a precipitate, and then weighing the precipitate. From the weight of the precipitate, the weight of its constituent elements can be calculated.

Quantitative analysis by titration is known as *volumetric analysis*. Usually a solution is prepared with a known amount of the material under test. The chemist then finds out how much of a standard solution of reagent reacts with it. The standard solution contains a known amount of reagent per litre, and its concentration is expressed in terms of *molarity*. A molar solution contains in each litre the equivalent weight of the substance in grams. (Equivalent weight is the amount of an element or radical that will combine with or replace one gram of hydrogen

or its equivalent.) Standard solutions of reagents have concentrations such as molar (M), 2M, M/2, M/10 and M/100.

In titration a known volume of one solution is placed in a flask, often with a pipette. A burette containing the other solution is placed above the flask so that the solution can run from it into the flask. Flow is controlled by means of a tap. In the majority of titrations a substance called an *indicator* is added to the solution in the flask in order to indicate the end-point of the reaction. It does this by changing colour. During titration solution is run into the flask from the burette until the solution in the flask just changes colour.

The volume of solution added is obtained by noting the levels of the solution in the burette before and after titration. As a result of titration we know that a certain volume of the solution of known strength reacts with a certain volume of the other solution of unknown strength. The strength of the other solution can thus be calculated. Standard titration reactions include those between acids and alkalis (neutralization), between oxidizing agents such as potassium permanganate and potassium dichromate and reducing agents such as iron(II) salts; and between iodine and sodium thiosulphate.

Weighing is such a routine operation in the chemical laboratory that sensitive weighing balances are a standard item. Although two-pan balances are still in use, the single-pan balance is now more common.

Whereas ordinary balances can measure to an accuracy of about a tenth of a milligram—one ten-thousandth of a gram—supersensitive microbalances can measure to a microgram—a millionth of a gram. One type is the quartz-fibre, or torsion balance, in which the balancing beam is returned to its equilibrium position by the twisting action of the fibre. Many microbalances operate electrically. They use the electromagnetic force developed by passing electric current through a coil to restore the equilibrium of a balancing arm. The amount of current necessary to restore balance is directly proportional to the weight of the sample which caused the imbalance. So weights can be read directly from a suitably calibrated ammeter.

The Modern Approach

The routine of the research chemist has been revolutionized in the last few decades by the introduction of sophisticated instruments for detection and measurement. Among these devices are the automatic microbalance mentioned above and automatic electronic titration equipment. In the latter, electrodes sense the concentration of ions in the solution being titrated; and they send signals via electronic circuitry to valves controlling the flow of the titrant from the burette. When the end-point is reached, marked by a particular concentration of ions, the titration is terminated. Automatic titration is one of several electrochemical methods of analysis which depend on such

things as variation in the conductivity of an electrolyte, the rate of transfer of ions, and the selective deposition of ions during electrolysis. Electrodes have been developed that are sensitive to specific ions.

Some of the greatest advances have been in spectrochemical analysis, which depends upon the measurement of wavelength and intensity of electromagnetic radiation. In *emission spectroscopy* the sample to be analysed is heated strongly so that it radiates light. The light is split up to give a characteristic spectrum from which the elements present can be identified. The relative intensities of the spectral lines of the various components are a measure of the relative amounts of the components in the sample. The flame photometer works on the emission principle and is widely used for rapid analysis. It is the sophisticated successor of the flame test. In the photometer a few drops of solution of the sample are sprayed into a standard flame. The intensity of the light emitted is measured by a photo-electric cell, and the result is read on a sensitive galvanometer. A filter is incorporated so that the dominant spectral line of the emitted light can be selected. The photometer is particularly useful for determination of the alkali and alkaline-earth metals.

The other major class of spectrochemical analysis is *absorption spectroscopy*. It is concerned with the examination of the absorption spectrum that results when light of various wavelengths is passed through a suitably prepared sample. The nature and intensity of absorption depend on the type and concentration of the substances present. Infra-red absorption techniques can be applied to almost all organic and inorganic compounds, but they are mainly used for identifying organic compounds. Ultra-violet techniques are used mainly for analysing aromatic organic compounds and biochemical compounds such as vitamins.

Investigation of the molecular structure of compounds is provided by X-ray and electron diffraction methods. When X-rays and electrons are passed through a substance, they are scattered, or diffracted, in a characteristic way. The resultant diffraction pattern reveals the structure of the substance. Irradiation with X-rays forms the basis of another method of analysis—X-ray fluorescence. This depends on the fact that, when an element is irradiated with X-rays of one wavelength, it emits secondary X-rays at a different wavelength which is characteristic of the element.

Mass spectroscopy is a particularly important technique. In this, a kind of spectrum is produced in which components in a mixture are sorted out according to their mass and charge. Briefly, the technique is to bombard the mixture with a beam of electrons, so as to cause its molecules to ionize. After being accelerated by an electric field, the ions are deflected by a magnet. They are deflected by differing amounts depending on their mass and charge, and can thus be separately

A chemical engineer supervising the operation of a pilot plant. Chemical engineers translate the chemical processes chemists work out in the laboratory into commercial processes. But before they build a full-scale plant they build a smaller-scale pilot plant to put their ideas to the test. Then if the pilot plant works satisfactorily, it will form the basis for the design of the full-scale plant.





Above: Distillation towers like this are a familiar part of the skyline at an organic chemical plant. This one, in Oklahoma, USA, makes polypropylene plastic.

Below: seated at a console in the control room of a large heavy chemical plant, a chemical engineer checks what is happening in critical areas of the plant. Around him are flow diagrams of the processes and arrays of controls and monitoring instruments.



detected. Mass spectroscopy is a very sensitive technique which can analyse qualitatively and quantitatively minute quantities of substances, such as those separated by gas chromatography. It is particularly useful for the analysis of complex organic molecules.

Chemical Engineering

The chemical industry is one of the largest and most important. All kinds of raw materials are processed into chemicals that can be used by other industries and made into consumer products. The chemical processes involved are based upon reactions first investigated in the chemical laboratory. But between the laboratory test-tube and a full-scale industrial plant there is a big gap.

This gap is bridged by the skills of the chemical engineer. It is his task to design and construct equipment that will carry out on a large scale the reactions conceived in the laboratory. He is particularly concerned when designing his plant with such basic problems as mass transfer, heat transfer, and fluid flow. Mass transfer involves the separation of components in mixtures by, for example, distillation or solvent extraction. Heat transfer characteristics of materials are a constant concern since heating, cooling and heat exchanging are almost inevitable in chemical processing. So are all aspects of gas and liquid flow—through pipes, ducts, valves, packed columns, filters, and so on.

The chemical engineer visualizes chemical processing—whatever it may be—as an interconnected sequence of separate operations. He calls these *unit operations*. Such operations aim to get the reagents into a suitable state and bring them together under suitable conditions, then separate the reaction product and bring it into a suitable state and purity for discharge. Typical unit operations include mixing, crushing, distillation, evaporation, filtration, leaching, crystallization, and solvent extraction. Each unit operation can be accomplished by standard types of equipment whose performance can be predicted; so the chemical plant becomes in essence a string of interconnected units.

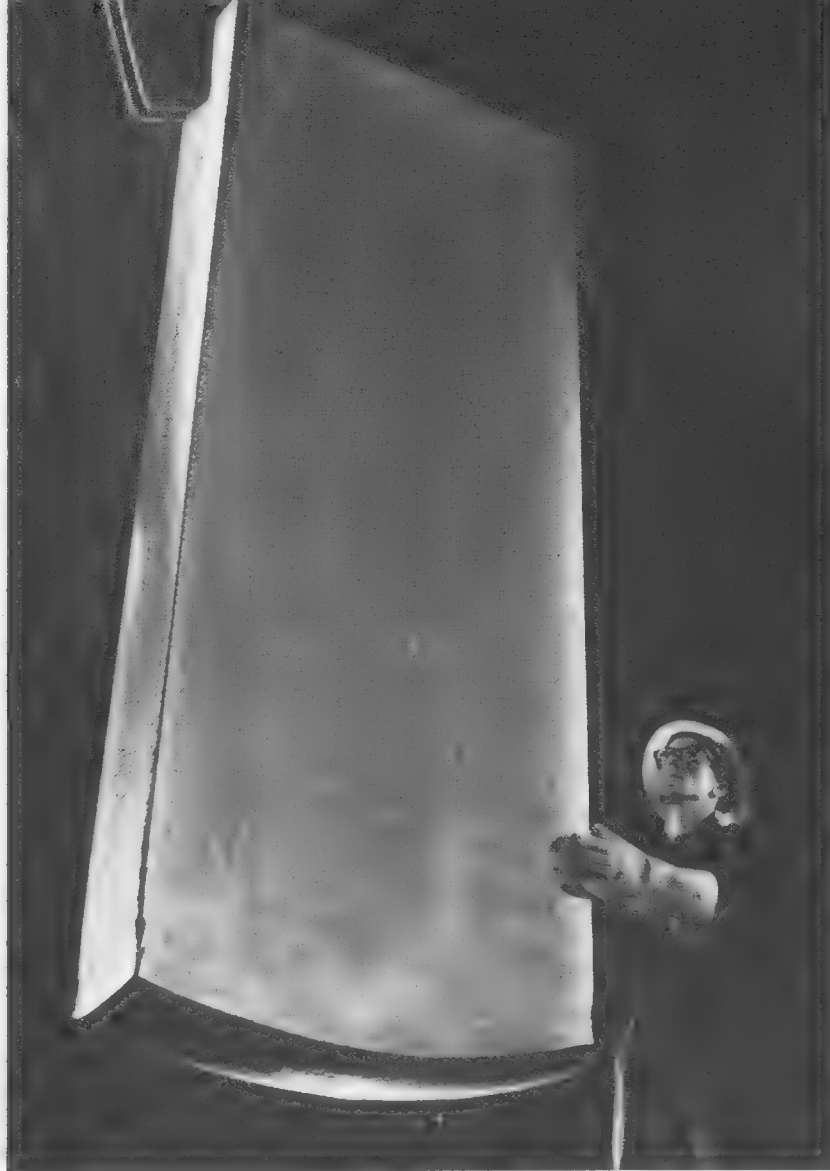
In a similar manner, the chemical engineer views the chemistry of a plant in terms of series of standard reactions, or *unit processes*. These include oxidation-reduction, nitration, sulphonation, esterification and polymerization. Again, each unit process has certain characteristics in common irrespective of what reagents are involved or products formed.

The safe and economic operation of any processing plant depends largely on its control systems. The emphasis today is on continuous, automatic operation. The opening and closing of valves, the flow of reagents, the temperature and pressure, the composition of products may all be controlled remotely and automatically by a computerized controller, acting on the continuous feedback of information from sensors located throughout the plant.

The Metals

Metals are some of the most useful elements known to man. They can be moulded, beaten, rolled, drawn or machined into almost any shape that is required. Here, quantities of molten steel are being poured into ingot moulds.





Aluminium

This lightweight metal (relative density 2.7) has been in commercial use for less than a century, but it is now second in importance only to iron and steel. More than 10 million tonnes are produced annually, of which nearly half is consumed in North America. Reasons for the widespread use of aluminium are not hard to find. It is a ductile metal that conducts heat and electricity well, and it is remarkably resistant to atmospheric corrosion. Though somewhat soft and weak in its pure state, it can readily be made into hard and strong alloys. Aluminium alloys have over the years replaced steel in many applications, resulting in a gain in corrosion resistance and lightness with no loss in strength. Unlike iron and steel, aluminium is not magnetic.

Typical uses of aluminium and its alloys include vehicle bodies, airframes and ships' superstructures; long-distance power transmission lines; curtain walling for skyscrapers; window frames, door furniture, and roofing; saucepans, kettles, and kitchen foil.

Sir Humphry Davy first suggested the existence of a metal 'aluminium' in the oxide

alumina in 1807. But not until 18 years later did Hans Oersted isolate a few specks of the metal. In 1886 Charles M. Hall in the United States and Paul Héroult in France independently developed the modern electrolytic reduction process by which aluminium is extracted from its oxide, alumina. The economics of aluminium production depends on the availability of cheap electrical power. For this reason, most aluminium reduction plants are associated with hydroelectric power schemes, some of which have been developed especially to provide power for aluminium smelting. The famous Kitimat power scheme in British Columbia was completed in the 1950s for this purpose.

Making Aluminium

Aluminium is the most plentiful metal in the Earth's crust, comprising some 8%. It is present in the rocks in such minerals as mica and feldspar, and in most clays. But the only important commercial source of the metal is *bauxite*, named after the French town of Les Baux, where it was first found. Bauxite contains alumina monohydrate (böhmite) and trihydrate (gibbsite), together with varying amounts of iron oxide, silica, and titanium dioxide. Pure alumina is extracted from bauxite ore by the Bayer process, which involves treatment with hot caustic soda solution. This dissolves alumina to form sodium aluminate, but the other minerals are unaffected. Cooling precipitates alumina trihydrate, which is then roasted to drive off the water.

The Hall-Héroult process consists of electrolyzing alumina dissolved in a mixture of molten cryolite (sodium aluminium fluoride, Na_3AlF_6) and calcium fluoride (CaF_2). The electrolysis, which takes place at a temperature of about 1000°C , yields molten aluminium at the cathode and oxygen at the anode. The anode consists of carbon rods, which combine with the oxygen to form gaseous carbon dioxide. The virgin aluminium produced by smelting is about 99% pure. But for special purposes 99.99% pure metal is required, and this must be obtained by electrolytic refining.

Above: A slab of aluminium which has been continuously cast in an open-ended, water-cooled mould.

Below: Breaking the hard crust that forms on an aluminium cell.



SURFACE FINISHING

Although most aluminium is used without special finishing, numerous protective and decorative finishes can be given to it. One of the commonest types of finishing processes is *anodizing*, a process in which the natural oxide film on aluminium is artificially thickened. This is done by making the aluminium the anode in an electrolytic cell with an acid electrolyte (such as sulphuric, oxalic, chromic or phosphoric acid). Magnesium and its alloys can also be treated by anodizing. Thickening the oxide layer by anodizing increases the corrosion resistance of the metal and also improves its durability.

The newly-anodized layer, which may be 100 to 1,000 times thicker than the original oxide film, is porous. But it can be sealed by treatment with boiling water. This treatment converts the oxide into its monohydrate, $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, which occupies more space than the simple oxide, causing the pores to be filled. In the newly anodized state the oxide film is receptive to dyestuffs, so that a colour-anodized finish can

be given. By impregnating the porous film with silver halides, the metal in effect becomes a photographic plate. Such plates are used widely to make printing plates for offset lithography printing. Aluminium oxide has good dielectric (insulating) properties, and electrical coils can be wound from anodized wire without the need for further insulation.

Another surface-finishing method is *chemical brightening*. This involves treating the surface with a strong acid or alkaline solution, often with the application of an external electric current. The effect of this treatment is to smooth down the microscopic 'hills' on the surface of the metal. It results in a much smoother, brighter and more reflective surface than that obtained by mechanical polishing. A so-called chemical conversion coating may be given to aluminium by treatment with acidic solution of phosphate or chromate. These coatings generally serve as a primer for subsequent painting.

Although some aluminium is used as smelted, most is alloyed with other elements to form alloys. Among the commonest alloying elements used are copper, silicon, magnesium and zinc. The resulting alloys are harder and stronger than pure aluminium. Further improvements in properties can be brought about by suitable heat treatment. *Duralumin* is one of many aluminium alloys that display the phenomenon of *age-hardening*. These alloys do not develop their optimum properties for some time—often taking several days. Both pure aluminium and its alloys are readily shaped by the usual metal-shaping methods such as casting, rolling, extrusion, forging and drawing.

Chemical Properties

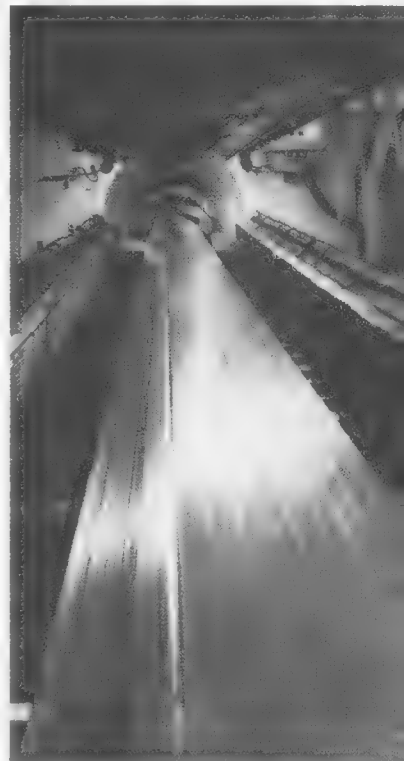
Aluminium belongs to Group 3A of the Periodic Table, and has an oxidation number of 3. It has a great affinity for oxygen, and is normally covered by an adherent oxide film. This oxygen affinity is utilized in the *thermite* process, in which iron oxide is mixed with powdered aluminium and ignited. A very vigorous reaction takes place as the oxide is reduced to metallic iron.

When aluminium is heated, it reacts readily with chlorine, sulphur, nitrogen and carbon, forming, respectively AlCl_3 , Al_2S_3 , AlN and Al_4C_3 . Although resistant to dilute sulphuric and hydrochloric acids and nitric acid, concentrated hydrochloric and concentrated sulphuric acids will attack it, forming the chloride and the sulphate. The metal will also dissolve in caustic potash and caustic soda solution, forming potassium or sodium aluminate (NaAlO_2).

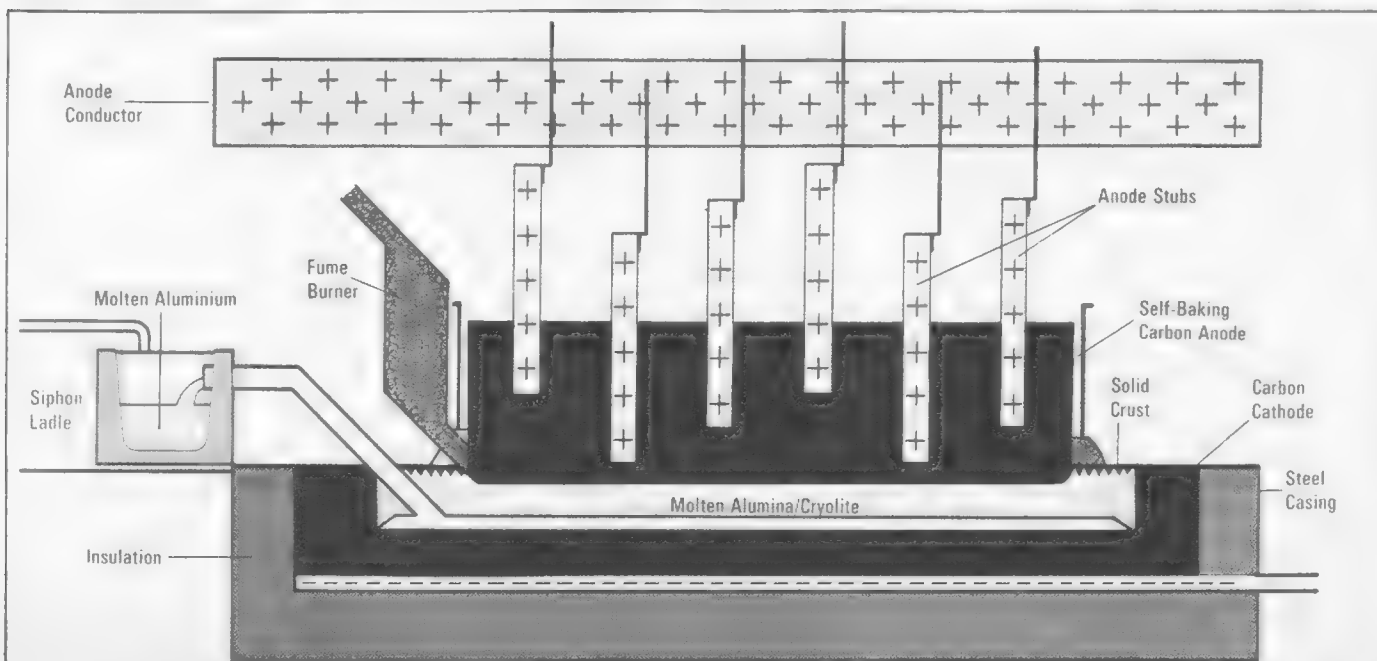
Aluminium chloride when anhydrous is extremely hygroscopic. It is a valuable catalyst for many chemical reactions, including the Friedel-Crafts hydrocarbon synthesis. The sulphate is used in water purification plants for precipitating colloidal matter. The double hydrated sulphate with potassium is known as potash alum $\text{K}_2\text{SO}_4 \cdot \text{Al}_2(\text{SO}_4)_3 \cdot 24\text{H}_2\text{O}$. It is a member of the series of alums having the general formula $M_2\text{SO}_4 \cdot N_2(\text{SO}_4)_3 \cdot 24\text{H}_2\text{O}$ where M is monovalent and N trivalent.

Like the metal, the oxide alumina, Al_2O_3 , and the hydroxide, $\text{Al}(\text{OH})_3$, dissolve in both acids, forming aluminium salts, and in alkalis forming salts known as aluminates. In other words, they are amphoteric.

A square-section aluminium extrusion emerging from a 5500-tonne press at Yennora, near Sydney, Australia. Aluminium is readily shaped by most metal-fabrication methods. In the extrusion process, a cylindrical aluminium billet is heated to 500°C, and a ram forces it through the hole in a steel die.



Cross-section of a typical aluminium electrolytic cell. The steel bath has a carbon lining which forms the cathode in the cell. A carbon anode dips into molten alumina solution. Molten aluminium collects on the floor of the cell beneath the anode and is drawn off periodically.





Iron and Steel



Of all the metallic elements, iron is the most important. It is very abundant, easy to extract from its ores, and can readily be made into our primary constructional material, *steel*. No metal approaches it in terms of tonnages used. Current world production of steel is about 600 million tonnes a year. This compares with only about 10 million tonnes for aluminium, the next most widely used metal.

Metallic iron itself is a greyish-white metal that is highly ductile and malleable, and therefore easy to shape. It is magnetic; most magnets contain iron, along with other magnetic elements like nickel and cobalt. By itself, iron is neither hard nor particularly strong. But with the addition of a little carbon it becomes steel and herein lies its great value. The addition of as little as one-tenth of one per cent of carbon to iron transforms it into a metal of high tensile strength, which can be made even tougher and harder by heat treatment. Other metallic and non-metallic elements can be incorporated in steels to give them enhanced properties, for example, corrosion resistance and even greater strength and toughness.

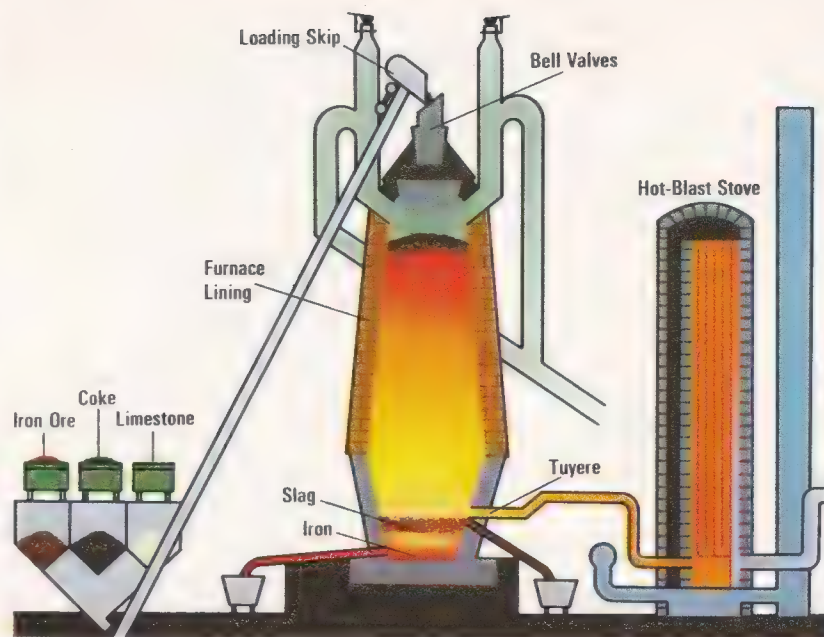
Iron has been widely used for at least 3000

years. When people discovered the advantages of iron over bronze for making weapons and implements a new era dawned—the Iron Age. It began in about 1200 BC in the near East and south-eastern Europe, and later elsewhere. Steel of a kind was made by the Romans, but it did not become available on a large scale until 1856, when Sir Henry Bessemer developed his process of steelmaking.

Iron Making

Iron is, after aluminium, the most abundant metallic element in the Earth's crust, comprising one-twentieth of it. In the Earth as a whole it is undoubtedly the most abundant element, for the central core of the planet is believed to be mainly iron, probably in a fluid state. Being a relatively reactive element iron is seldom found in a native state, though it can sometimes be found alloyed with nickel. Some iron-nickel alloys have been found that have reached the Earth as meteorites.

Iron compounds are widespread in the Earth's crust, and they have become concentrated in workable mineral deposits in many parts of the world. Among the many iron-bearing minerals are the oxides *haematite* (Fe_2O_3) and *magnetite* (Fe_3O_4); the hydrated oxide, *limonite* ($\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$); the carbonate, *siderite* (FeCO_3); and the sulphide, *iron pyrites* (FeS). The latter is used as a source of sulphur, not iron, but the others are all important iron ores. Haematite, often called *kidney iron ore* because of the way it sometimes crystallizes, is deep red when pure. Magnetite is black and is magnetic. Limonite is brown and is often called *bog-iron ore*. Russia is the world's largest producer of iron ore, with an annual output of nearly 200 million tonnes. This is double the output of the United States, the



A blast furnace. Iron ore, coke and limestone are charged into the furnace through so-called bell valves, which allow material to enter without letting the furnace gases escape. Hot air from hot-blast stoves is blasted through the tuyères and causes the coke to burn fiercely, raising the temperature in the lower part of the furnace to over 1500 °C. The iron ore is reduced to iron, which runs to the bottom of the furnace. Impurities combine with the limestone to form a slag, which floats on top of the iron. Iron and slag are tapped periodically.

next largest producer. Most iron ore is obtained by open cast surface mining, though some is worked in deep-level underground mines.

Because they come from the ground, most iron ores are associated with gangue, worthless earthy material which must subsequently be removed. This may be done by washing; or it may be done magnetically. Often the ore is roasted to drive off water and, in the case of carbonate ores, carbon dioxide. The ore is usually crushed during preparation, resulting in a fine dust. To prevent trouble in later operations the crushed roasted ore is heated strongly, or sintered. This treatment makes it coalesce into larger lumps. Sometimes fine ore dust is mixed with clay, formed into shapes, and baked, a process called *pelletization*.

Iron is produced from the ore in *blast furnaces*. These are tall structures, 30 metres or more high and about 9 metres in diameter at the base. The essential reaction that takes place in a blast furnace is one of reduction. The iron oxide is reduced to metallic iron by a series of reactions involving carbon monoxide and carbon, which is added to the furnace in the form of coke. The coke, burning fiercely in the air blasted into the furnace, also provides the heat to melt the charge. Limestone is introduced into the furnace to act as a flux. It combines with impurities associated with the iron ore, and enables them to melt at a lower temperature than they would otherwise, to form a molten slag. This floats on top of the molten iron. The furnace is tapped periodically to allow the molten metal and slag to be removed.

Pig, Cast and Wrought Iron

The iron tapped from the blast furnace is often carried in huge travelling ladles to an adjacent steel-making plant. Or it may be poured into moulds called *pigs*, from which it gets its name, *pig iron*. Pig iron is by no means pure; it contains up to four per cent carbon

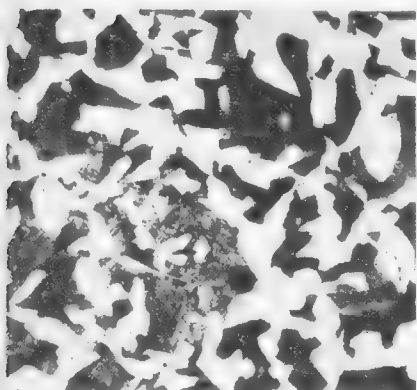
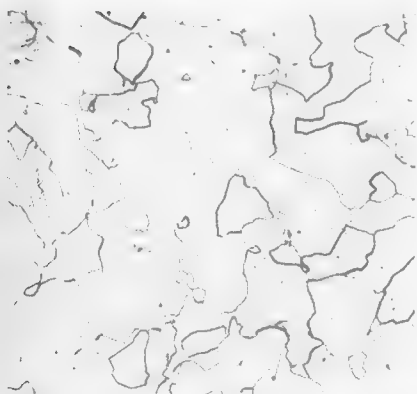
Top left: The famous iron-ore mining region known as Iron Knob, in South Australia.

Bottom left: A steel casting emerging from an annealing furnace. Annealing is one form of heat treatment, which relieves stresses in the metal.

Below: An electric-arc furnace, showing the red-hot carbon electrodes from which the arc is struck.



The three photographs below are micrographs of certain types of steels. (Micrographs are photographs taken through a microscope.) The specimens of steel were etched to make their grain boundaries stand out. Below: The typical ferrite structure of steel with scarcely any carbon in it. (x200)



Above: 0.3% carbon steel, showing a ferrite and pearlite structure. (x 200)

Below: Hyper-eutectoid steel (one with a carbon-content greater than 0.8%), showing a pearlite and cementite structure. (x 400)



STRUCTURE OF STEEL

Pure iron can assume three structural forms, depending on the temperature, termed *alpha* (up to 911°C), *gamma* (up to 1392°C) and *delta* (from 1392°C to its melting point, 1539°C). In normal iron and steel metallurgy the first two forms are of greater importance. In steel both these two structural forms of iron are usually present, they form two of the three main components, or *phases*, in steel. The alpha phase is practically pure iron, while the gamma phase contains dissolved carbon. The third main phase in steel is a compound of iron and carbon—iron carbide, Fe_3C . The carbide phase is termed *cementite*, the alpha-iron phase, *ferrite*; and the gamma-iron phase, *austenite*.

Under normal conditions austenite exists above 727°C, the so-called critical temperature. Steel below 727°C consists of a mixture of ferrite and cementite. The cementite is often present in layers sandwiched between layers of ferrite, giving rise to a distinctive structure called *pearlite*. Up to a composition of about 0.8% carbon, steel has a structure of ferrite and pearlite, the amount of pearlite increasing as the carbon content increases. At carbon contents greater than 0.8%, the structure is pearlite and cementite, the amount of cementite increasing as the carbon content increases. The properties of ferrite, cementite and pearlite differ greatly, which explains why steels of different carbon

content have different characteristics. Ferrite, being nearly pure iron, is soft and ductile; cementite is strong, hard, but brittle; while pearlite has properties in between. Thus steels with low carbon content (more ferrite) will in general be weaker, more ductile, and softer than steel with high carbon content.

The type of structure and properties mentioned above refer to steel that has been allowed to cool slowly. When it is heated and then cooled rapidly a different structure results, which greatly modifies the steel's properties. This process, called *quenching*, is one form of heat treatment. The steel is heated above its critical temperature, and austenite forms. Then it is plunged into water or oil and cools rapidly. The austenite does not have time to change into ferrite and cementite, but becomes a kind of supersaturated ferrite, known as martensite. The crystal lattice of martensite is very distorted, giving rise to great hardness and brittleness.

To remove the unwanted brittleness without sacrificing too much of the hardness, the quenched steel must be *tempered*. This means heating it to a temperature of 300°C or so and allowing it to cool in the air. Tempering relieves the internal stresses in the martensite and allows the formation of a fine structure consisting of cementite particles embedded in a ferrite matrix. This structure imparts toughness to the steel.

and smaller amounts of other elements, which may include manganese, phosphorus, silicon and sulphur.

With slight refining, however, it becomes suitable for making iron castings. At the foundry pig iron is remelted in a *cupola*, which is a kind of miniature blast furnace. Iron scrap and other metals may be added to the pig iron to give improved properties. The iron produced, known as *cast iron*, is very fluid when molten and is thus easy to cast. The commonest cast iron, called *grey cast iron*, is strong, easy to machine and resistant to shock; but it is brittle.

Another form of iron sometimes produced from pig iron is *wrought iron*. It consists of almost pure iron mixed with threads of slag. It is made by remelting pig iron in a furnace with iron ore. Impurities in the iron combine with the iron ore to form a slag. The temperature is raised, and the carbon in the iron reacts with the iron ore. The resulting pasty iron-slag mix is then hammered or pressed to squeeze out excess slag. Although little used today, wrought iron nevertheless has excellent properties. It is tough and is highly ductile and malleable; it is resistant to shock and more resistant to corrosion than ordinary iron and steel.

Iron Chemistry

Iron is a typical transition element belonging to Group 8B of the Periodic Table. Its chemistry is similar to that of chromium and manganese, which precede it in the Table. Like these elements it exhibits two oxidation states *iron(III)*, or *ferric*, and *iron(II)*, or *ferrous*. It combines directly with chlorine and the other halogens, carbon, boron, sulphur, phosphorus and silicon.

With dilute sulphuric and hydrochloric acids iron forms iron(II) salts, liberating hydrogen. With dilute nitric acid, however, ammonium nitrate, NH_4NO_3 , and iron(II) nitrate, $\text{Fe}(\text{NO}_3)_2$, are formed. Concentrated nitric acid renders iron passive because, being a powerful oxidizing agent, it causes a thin protective film of Fe_3O_4 to form over the iron.

Iron(II) sulphate crystallizes as a heptahydrate, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, which is known as *green vitriol*. (Copper sulphate crystals are called *blue vitriol*.) Iron(II) sulphate is widely used in the manufacture of inks, fertilizers and pesticides. It is used as a reducing agent in chemical processes. It is readily oxidized to iron(III) sulphate, $\text{Fe}_2(\text{SO}_4)_3$, which is used as a mordant in dyeing and as a coagulant in water-purification plants. With ammonium sulphate it forms an alum, $\text{Fe}_2(\text{SO}_4)_3 \cdot (\text{NH}_4)_2\text{SO}_4 \cdot 24\text{H}_2\text{O}$.

Iron readily combines with the oxygen in the air to form iron(II)diiron(III) oxide, Fe_3O_4 , a strong magnetic, black powder with a high melting point (154°C). Iron(III) oxide, Fe_2O_3 , prepared by burning iron(II) sulphate, is a soft red powder, used by jewellers for polishing (jewellers' rouge) and in cosmetics as a pigment. Hydrated iron(III) oxide, $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$, is the familiar compound *rust*. It forms on iron exposed to damp air as a result of an electrolytic process. Because iron is impure, tiny electrolytic cells are set up on it in the presence of moisture. The probable mechanism is as follows: at anodic (electrically positive) areas iron dissolves as iron(II) ions, while in cathodic (electrically negative) areas hydrogen forms, and hydroxyl ions (OH^-) form. The iron(II) and hydroxyl ions combine to form iron(II) hydroxide, $\text{Fe}(\text{OH})_2$, which immediately reacts with

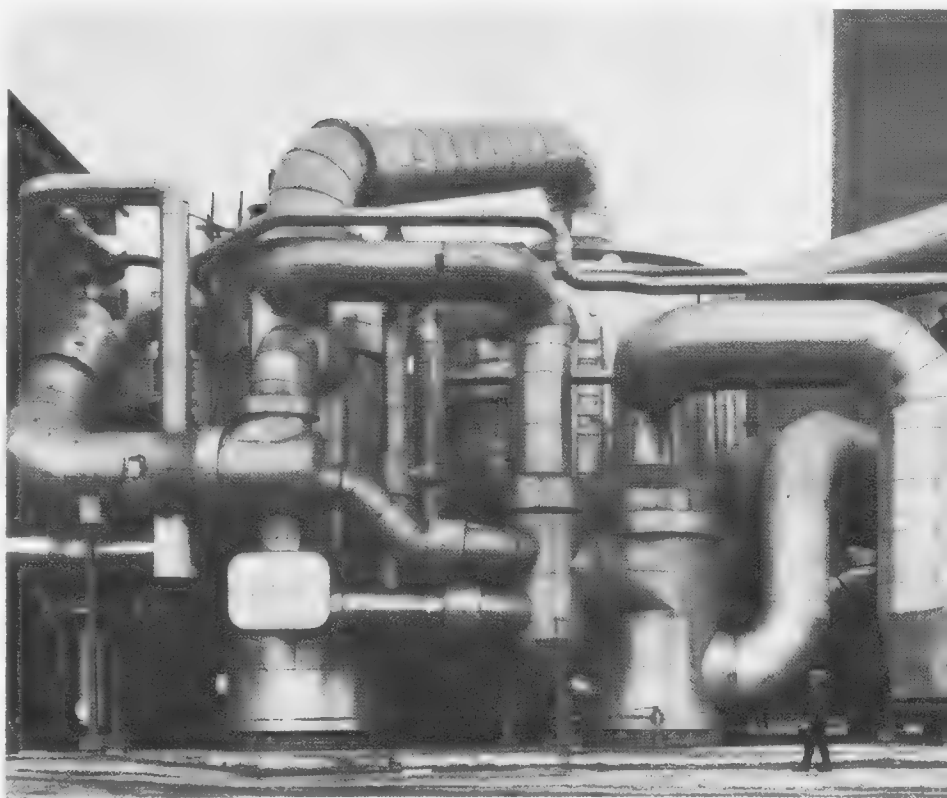
carbon dioxide in the air to form iron(II) carbonate, FeCO_3 . The air then oxidizes the carbonate into iron(III) oxide, Fe_2O_3 , which hydrolyses at once to rust, $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$.

Making Steel

The basic process of steel-making is one of removing the bulk of the carbon and other impurities from pig iron and then adding controlled amounts of other ingredients to yield an alloy of the desired properties. This process of refining is carried out at high temperatures in a furnace. Various types of furnace are used. In the *open-hearth* furnace the charge is melted on a shallow hearth open to the furnace flames, which are provided by burning oil or gas. In the *arc furnace* the charge is melted on a shallow hearth by heat developed by an electric arc struck between carbon electrodes and the charge. In the *converter*, a pear-shaped tiltable vessel, air or oxygen is directed through or on to the charge, heat being produced as a result of reactions taking place inside.

Most steel is produced these days by the open-hearth and the *basic-oxygen* processes. The latter is a development of the original large-scale steel-making process invented by Henry Bessemer in 1856. Little Bessemer steel is made today, but the process is historically interesting: air is blown through molten pig iron to oxidize impurities. The electric-arc process is widely employed to make high-purity alloy steels. In all steelmaking these days steel scrap is used as well as pig iron. In fact with electric furnaces the charge is invariably steel scrap only.

A diagram of the open-hearth furnace appears on this page. Up to 12 of these furnaces may be installed in a row at a steel-works so that they can be serviced by the same equipment. The largest furnaces can refine 600 tonnes or more of steel at one *heat* (firing). Most open-hearth furnaces are of the *basic* type, being lined with basic refractory bricks of calcined dolomite ($\text{CaO} \cdot \text{MgO}$) or chrome-

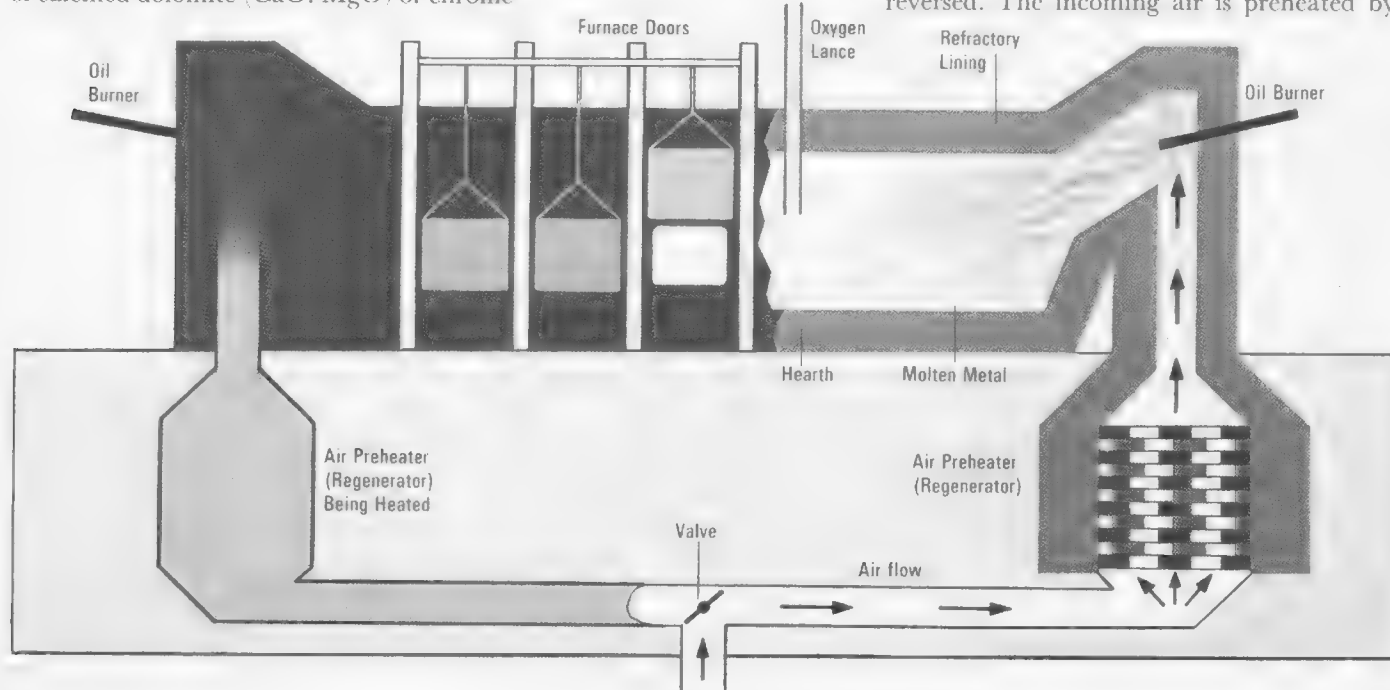


The piping and reactor vessels of this sulphuric-acid making plant are fabricated in stainless steel, which resists corrosion strongly.

Layout of an open-hearth steel-making furnace. The charge is melted in a shallow hearth which is open to the furnace flames. The incoming air is preheated by the hot brickwork of one of the regenerators. The brickwork in the other regenerator is being heated by the exiting furnace gases.

magnesite ($\text{Cr}_2\text{O}_3 \cdot \text{MgO}$). A basic material such as limestone must be added to assist slag formation in this type of furnace. If the furnace lining is acidic, however, an acidic material such as silica must be used. If the slag-former were acidic and the furnace lining basic, or vice versa, the lining would rapidly be destroyed.

The charge for the basic open-hearth furnace consists of pig iron, steel scrap, iron ore, and limestone. Fuel is sprayed into the furnace and burns in hot air coming from one of the *regenerators* beneath the furnace floor. The flames play on the charge and melt it, and the hot flue gases exit via the second regenerator, which is thereby heated. Every 20 minutes or so the direction of flow of air and flue-gas is reversed. The incoming air is preheated by





the regenerator previously heated by the flue gases.

As the charge melts and the temperature rises to over 1500°C , the iron-oxide ore reacts with silicon, manganese and phosphorus impurities in the iron to form their oxides, leaving iron. The oxides pass into the lime slag. The iron-oxide ore also oxidizes the carbon in the iron, with the formation of carbon monoxide and a little carbon dioxide, which bubbles from the molten metal and slag. Oxidation of the impurities is usually accelerated these days by means of a jet of oxygen, which is directed on to the surface of the molten mass.

The steel is sampled and analysed periodically to determine its composition, and when the required carbon content and impurity levels are reached, the furnace is tapped and the molten metal run into ladles. Certain deoxidizing agents such as ferromanganese or aluminium are added to the molten metal to remove oxygen from it. This prevents the formation and escape of carbon monoxide gas while the steel is cooling which would otherwise lead to weakness in the solidified metal. Other elements may also be added in the ladle to bring the steel to the desired composition. Then the molten steel is poured into ingot moulds, a process called *teeming*. When they have solidified, the ingots are stripped from their moulds and sent for shaping.

The basic-oxygen process is rapidly outstripping the open-hearth process. It was first developed in Austria in 1949 at steel-making plants in Linz and Donawitz, and is often called the L-D (Linz-Donawitz) process. It uses a basically lined, pear-shaped converter, which may have a capacity of up

Above: Steel rod cooling after emerging from bar and rod coiling machines. Vast quantities of steel rod are used, for example, in the construction industry to reinforce concrete.

Automatic rolling mill for steel sheet. A red-hot, thick steel slab enters the mill at one end and is progressively reduced in thickness as it passes between a series of rollers.

Control room for an automatic rolling mill. The whole operation is controlled by a computer, which automatically and continuously regulates the separation of the rollers to give sheet of precisely the right thickness.

to 300 tonnes of steel. The converter is so mounted that it can be tilted either way for charging and tapping. A water-cooled tube or lance projects vertically into the furnace and delivers a stream of oxygen at supersonic speed. A hood can be lowered over the mouth of the converter during processing to carry off the fumes produced.

Steel scrap and hot metal are charged into the furnace. The oxygen lance is lowered, and refining begins as a supersonic jet of oxygen is directed onto the surface. Then limestone, iron ore, and fluorite (CaF_2) are added, the latter acting as a flux to produce a very fluid slag. Much the same kind of reactions take place in the converter as in the basic open-hearth process. The great advantage of the basic-oxygen process is that refining takes place in a matter of 20 minutes or so. The whole operation—charging, lancing, and emptying—can be accomplished in between 30 and 60 minutes, depending on the size of the furnace. This compares with six hours or more for an open-hearth furnace. And the quality of basic-oxygen steel is at least as high as open-hearth steel.

The electric furnace is used to make high-



quality alloy steels because refining can be closely controlled. The temperature is easily regulated, steel scrap of precise composition is used, and there is no contamination of the steel by combustion products from burning fuel. The arc furnace has a saucer-shaped hearth with a kind of spout projecting on one side. The furnace is mounted on rockers so that it can be tilted for emptying via the spout. It has a removable arched roof, in the top of which are three thick graphite (carbon) electrodes.

The roof is lifted off while steel scrap, lime, iron ore and fluorite are charged into it. It is then replaced, the carbon electrodes are lowered, and an arc is struck between them and the charge. The heat produced by arcing melts the charge, and refining takes place. Oxygen is often supplied by a lance to assist oxidation. Alloying elements may be added before the furnace is tilted and emptied. For highest quality steels, the process is extended. After the initial slag formation, the slag is poured off, and deoxidizing agents are added to the remaining metal. More lime and fluorite are added to form a slag that dissolves any remaining impurities. Alloying elements are then incorporated to bring it to the desired composition.

Another type of electric furnace is used on a small scale. Called the *induction furnace*, it develops heat to melt the charge by electromagnetic induction. Alternating electric current is passed through coils surrounding the furnace. They induce eddy currents in the metallic charge which cause it to heat up.

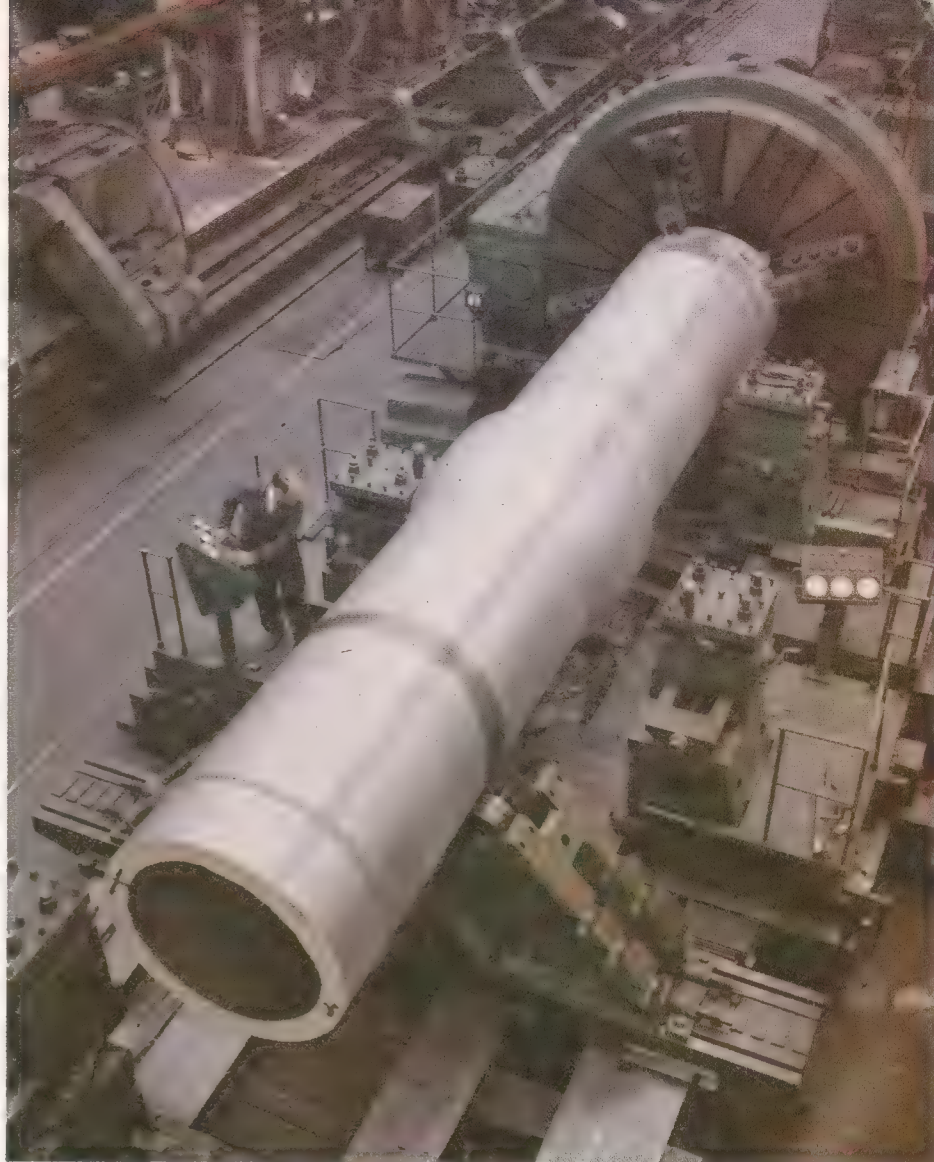
Carbon and Alloy Steels

The two major kinds of steels are carbon steels and alloy steels. *Carbon steels* contain from 0.08% to about 1.5% carbon, and their properties depend on the amount of carbon they contain. *Alloy steels* also contain carbon of course, but their properties depend primarily on the presence of the alloying elements rather than on the carbon content.

Carbon steels do contain small amounts of other elements besides carbon. These elements invariably include manganese, silicon and copper, and may also include aluminium, boron, chromium, cobalt, nickel, titanium, tungsten, vanadium or zirconium. Unspecified but relatively low amounts of such elements enter or are introduced into the steel during production processes (such as de-oxidizing). The four main grades of carbon steels are low-carbon (0.08–0.5% carbon); mild (0.15–25% carbon); medium-carbon (0.25–0.5% carbon); and high-carbon (0.5–1.5%) steels. Low-carbon steels are tough, ductile, and easy to shape and weld. As the carbon content increases, the steels become progressively stronger and harder. Their hardness and other properties can often be greatly improved by heat treatment. Typical uses include low-carbon steel for car bodies; mild-steel for structures; medium-carbon steel for propeller shafts and nuts and bolts; and

high-carbon steel for rails, cutting tools, razor blades and springs.

The addition of alloying elements to steel enables special properties to be imparted to the metal, such as corrosion resistance (which ordinary steel lacks), springiness, added strength, and toughness. Among alloying elements chromium and nickel are the most important. Their addition not only makes steel stronger, but also makes it corrosion-resistant, when it becomes known as *stainless steel*. The best-known type of stainless steel contains 18% chromium and 8% nickel, and is commonly referred to as 18/8 stainless steel. It cannot be hardened by heat treatment, but does harden when cold-worked. Plain chromium stainless steels contain no nickel at all and up to 30% chromium. Other major alloying elements are manganese, vanadium, molybdenum and tungsten. Manganese confers great toughness, impact resistance and hardness to steels. Vanadium refines the structure of steels and makes them more able to resist shock and fatigue. It is used in forging steels and tool steels. Molybdenum imparts strength and temperature resistance. It too is often incorporated in tool steels, together with tungsten. Tool steels are so formulated that they can run at very high speeds without losing the hardness of their cutting edge when they become hot.



Above: A pressure vessel being machined on a gigantic lathe. Turning on a lathe is one of the most common machining operations used for finishing pieces of metal roughly shaped by other processes.

Below: An electrical resistance welding set-up, showing the disc-like electrodes which not only carry the current but also apply the pressure.



Copper

Like its close relatives gold and silver, copper has been known to Man from early times, probably as long as 10,000 years ago. All three metals can be found native in the ground, and undoubtedly the early civilizations used native copper to make utensils and ornaments. They found that the attractive reddish-brown metal was easy to shape and did not readily lose its shine. In about 4000 BC copper was first smelted (probably by accident at first) and its use became more widespread. Some five centuries later in places where copper and tin ores occurred together, *bronze*—the hard alloy of copper and tin—was accidentally produced. Soon early metallurgists were deliberately smelting copper and tin ores in suitable proportions to yield bronze of desired quality. The increasingly widespread use of bronze between about 3000 and 1000 BC caused this period of history to be named the Bronze Age. It was succeeded by the Iron Age. In classical times the purest copper was smelted in Cyprus, and the chemical symbol for copper, Cu, comes from the Latin word *cuprum*, meaning Cyprian metal.

Copper is still valued today for its attractive appearance, ease of shaping, and resistance to corrosion. It can be shaped by rolling, pressing, forging and drawing. It is so ductile that it can be drawn into wire 0.005 centimetre in diameter; so malleable that it can be hammered into strips 0.0025 centimetre thick. Joining copper parts together also presents no problem, for the metal is easy to solder, braze and weld. Most of copper's many alloys—with tin (*bronze*), zinc (*brass*), nickel (*cupronickel*)—share copper's desirable qualities to a greater or lesser extent.

One thing they do not share, however, is copper's most notable quality—its very high electrical conductivity. Only silver is superior to copper in this respect, but its cost and scarcity precludes its use on a large scale. Half of the 6–7 million tonnes of copper produced annually in the world is used by the electrical industry for wiring, contacts, and the like. Copper is also a superb heat conductor, again being second only to silver in this respect. It is therefore used in heat exchangers and for such things as car radiators, kettles and saucepans.

Extraction

Native copper is rarely found today and is usually of geological interest only. Workable deposits of copper minerals are found more widely. The most important copper ores are the sulphides, which include *chalcocite*, or *copper glance* (Cu_2S); *chalcopyrite*, or *copper pyrites* (CuFeS_2); and *bornite* (Cu_5FeS_4). Among

other important sources of copper are the oxide *cuprite* (Cu_2O) and the basic carbonates *azurite* and *malachite* ($\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$). Often the copper sulphides occur intimately mixed with other sulphide minerals, such as those of nickel and iron, as in the famous deposits at Sudbury, Ontario. These ores often yield appreciable quantities of precious metals as well (see page 199).

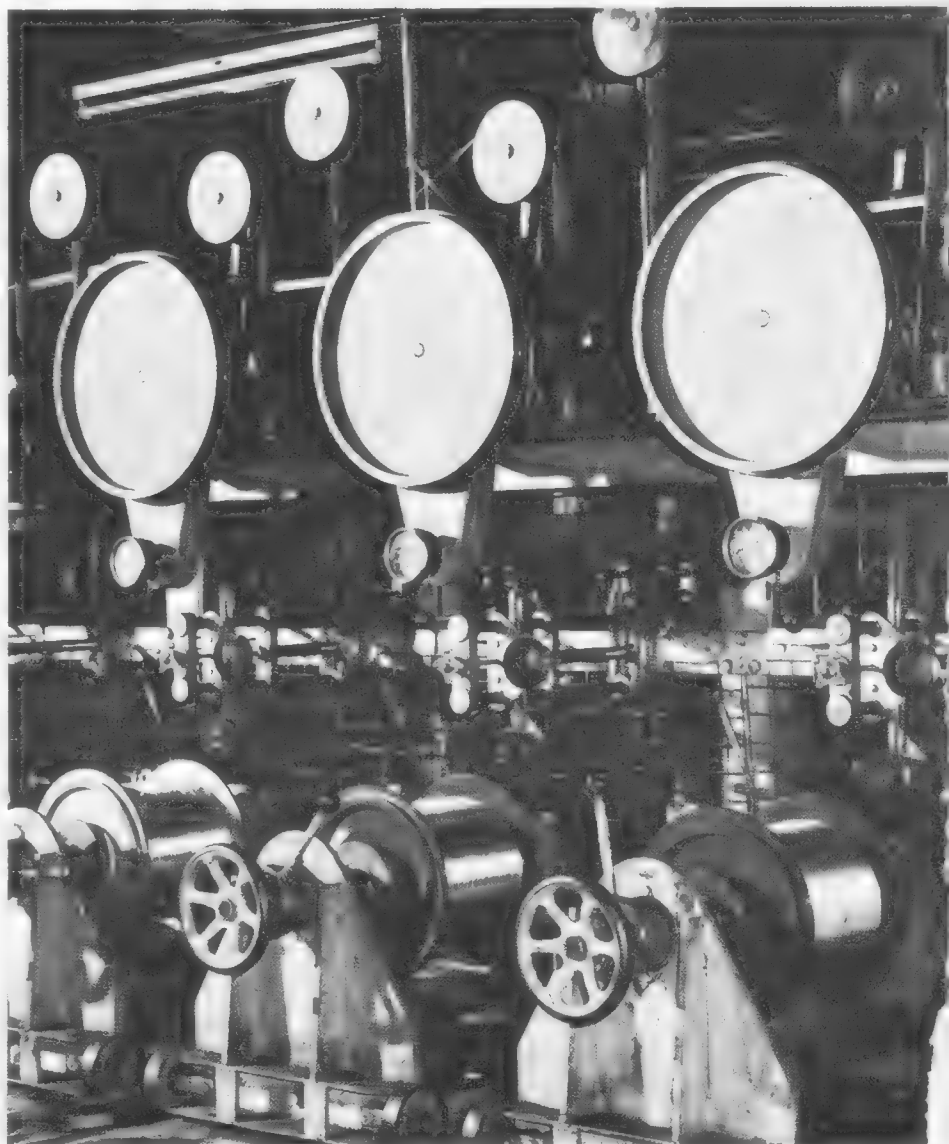
The United States is the world's leading copper producer, with major deposits at Butte in Montana and Bingham in Utah. The Bingham Canyon Copper Mine is considered the world's largest excavation and is more than three kilometres wide and 700 metres deep. Some 320,000 tonnes of ore and overburden are extracted from the opencast mine daily. Copper ores are also worked by underground mining, as at El Teniente, in Chile, and in the famous Copperbelt region on the Zaïre-Zambia border. Chile and Zambia follow the United States in copper output.

Refining

The processing of copper ores takes place in several stages; a number of methods are used, depending on the type of ore being handled. The extraction of copper and nickel

Right: The electrolytic cell room in which copper is refined by electrolysis. The impure copper obtained by smelting is made into anodes, which gradually dissolve. Pure copper is deposited on the cathodes.

Below: The most important single use of copper is in the form of wire. Wire is made by a drawing operation on machines like these. It is drawn cold, for copper has excellent ductility even at ordinary temperatures.





COPPER ALLOYS

With zinc, copper forms a series of alloys called *brasses*. When brasses contain less than 36% zinc, they are malleable and ductile when cold, and they can be shaped cold with ease. Cartridge cases are often made with 70/30 brass (containing 30% zinc).

Brasses containing more than 36% zinc are much harder and stronger. Up to 36% zinc the alloy is a single-phase solid solution. Above 36% it is a two-phase solid solution, the phases being termed alpha and beta. One of the most widely used of these so-called alpha-beta brasses is 60/40 brass, better known as Muntz metal. Alpha-beta brasses are generally shaped hot.

Alloys of copper with tin are called *bronzes*. However, the term is also sometimes applied to copper alloys with other elements which contain no tin at all. The commonest bronze is that used for coinage. A typical composition would be 97% copper, 0.5% tin and 2.5% zinc. Alloys containing less copper and more zinc, known as *gunmetals*, are in widespread use—for marine applications for example. The so-called Admiralty gunmetal contains 88% copper, 10% tin and 2% zinc.

Phosphor bronzes usually contain less than 0.5% phosphorus with about 6% tin. Aluminium bronzes contain no tin at all, but up to about 12% aluminium. Silicon bronzes contain no tin either. All of these bronzes have excellent corrosion resistance and strength.

With nickel, copper forms an extensive range of alloys, the most familiar being the *cupro-nickels*, which contain up to 30% nickel. The 75% copper, 25% nickel alloy is used commonly for 'silver' coinage. So-called *nickel silver* containing copper, nickel and zinc, is widely used as a base metal in silver plating, the product being termed electroplated nickel silver. Among the other interesting copper alloys is *Monel*, which is a natural alloy obtained by smelting the nickel-copper Sudbury ore directly.

from the mixed-sulphide Sudbury ore is outlined on page 198. Normally sulphide ores are separated from the gangue, or earthy material they are associated with, by selective *flotation*. The ore is finely ground and mixed with water and a frothing agent; the mineral particles are preferentially attracted by the bubbles and floated away. The copper concentrate from this so-called mineral-dressing operation is roasted to convert iron into iron oxide; to expel some of the sulphur; and to drive off volatile matter containing, for example, antimony and arsenic. Next the roasted ore is transferred to a reverberatory furnace, where the iron oxide combines with silica in the ore to form a slag, leaving fused sulphides of iron and copper—a mixture known as *matte*. Air is then blasted through the molten matte in a converter to burn away the sulphur. Silica is added to extract further impurities and form a slag. The resulting crude, 'blister' copper is usually then refined to high purity by electrolysis, using an electrolyte of acidified copper sulphate.

Oxide ores of copper are usually processed by *leaching*, or treatment with a substance that dissolves the mineral but not the associated impurities. Dilute sulphuric acid is often used, resulting in a weak solution of copper sulphate. Electrolysis of this solution will yield the pure metal.

Chemical Properties

Copper is a typical transition metal in Group 1B of the Periodic Table, which also includes silver and gold. It has many characteristics of these metals, but is less corrosion resistant and more reactive generally. In its compounds it may be monovalent, copper(I), or divalent, copper(II). The divalent compounds are the commonest and most stable.

In air, copper slowly tarnishes, but if heated to red heat, black scales of copper(II) oxide, CuO , form. On exposure to the air for several years, copper gradually becomes covered with a beautiful blue-green *patina*, which consists of a basic copper sulphate, $[\text{Cu} \cdot 3\text{Cu}(\text{OH})_2] \text{SO}_4$. Nitric acid attacks copper, forming copper nitrate, $\text{Cu}(\text{NO}_3)_2$. Hydrochloric acid attacks it when hot and concentrated, forming the complex H_3CuCl_4 . Dilute sulphuric acid reacts with it in the presence of oxygen to form copper sulphate, CuSO_4 .

Copper sulphate is the most familiar of copper compounds, having a beautiful blue colour, which is due to the presence of the hydrated copper(II) ion $\text{Cu}(\text{H}_2\text{O})_4^{2+}$. When copper sulphate is heated and water is driven off, it becomes white. Ammonia forms a similar complex with the copper(II) ion. When ammonia solution is added in excess to copper sulphate solution, a deep blue colour results, which contains the complex tetraammine copper(II) sulphate, $\text{Cu}(\text{NH}_3)_4\text{SO}_4 \cdot \text{H}_2\text{O}$. Tetraammine copper(II), or cuprammonium, compounds have been used to make rayon, because they can dissolve cellulose.

A Benin bronze. The kingdom of Benin was an advanced civilization of the region of West Africa which is now Nigeria. It was at its peak between about 1400 and 1600, although it continued until the British conquered it in the 1890s. Benin bronzes are among the best art Africa has ever produced.



Nickel

Nickel is one of the metals of the first transition period of the Periodic Table, sandwiched between cobalt and copper. It has a combination of valuable properties. Attractive to look at, it takes a high polish and does not tarnish. It is highly ductile and malleable, so shaping it either hot or cold presents no difficulty. It is also magnetic.

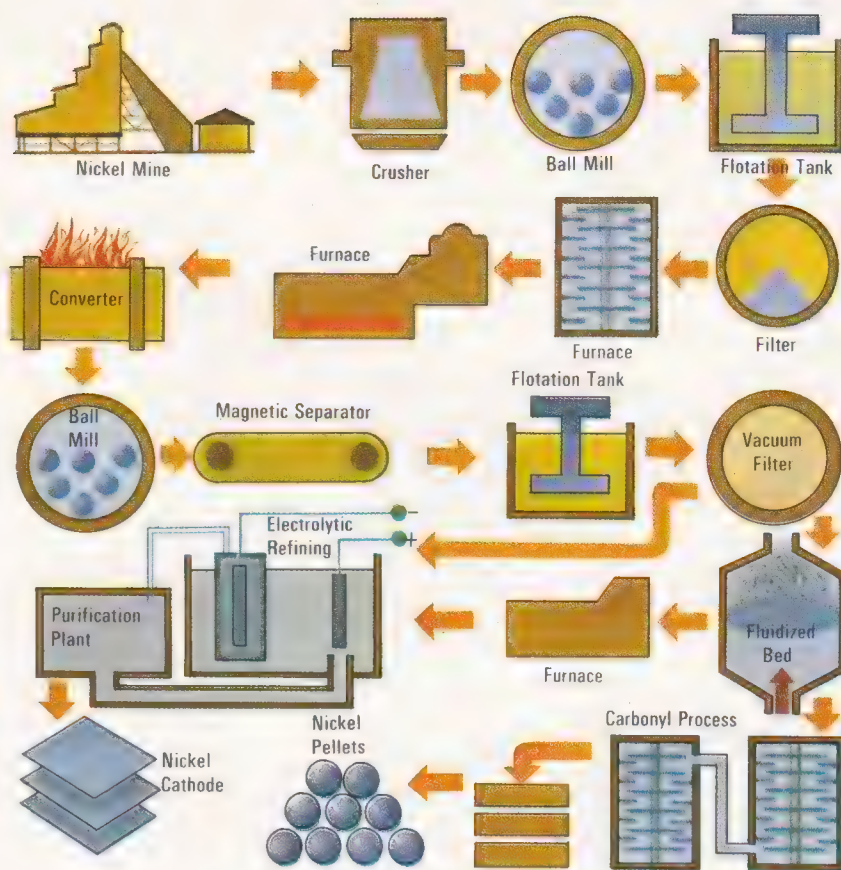
One of the greatest uses of nickel is in electroplating. It is invariably used as an undercoat for chromium plating. Nickel is also a major alloying element in ordinary *stainless steel* (known as 18/8 because it consists of 18% chromium, 8% nickel, with the balance mainly iron). Another well-known use of nickel is in coinage. It is alloyed with copper to form the *cupronickel* alloys used today for so-called 'silver' coins. The cupronickel used for coinage contains about 25% nickel to 75% copper. Nickel and copper form many other useful alloys, which are characterized by high strength and corrosion resistance. *Monel metal*, which contains about 66% nickel, has many marine uses since it resists even sea-water corrosion. *Nickel silver* is used as a base for silver plating—it contains mainly copper and nickel (up to 30%).

One of the most interesting of its alloys is *invar*, which is a nickel-iron alloy containing 36% nickel. It has exceptionally low thermal expansion, so it is used for the balance wheels of watches, for measuring scales, and for precision instruments, whose performance would be affected by changing temperature. Its magnetic properties are utilized in such alloys as *permalloy* (86% nickel, 21% iron) and *alnico* (a typical composition of which would be 14% nickel, 8% aluminium, 24% cobalt, 3% copper, and 41% iron).

Although used mainly in alloys, nickel metal has other uses too. When finely divided, it acts as an excellent catalyst for many chemical reactions, especially those involving hydrogen. It is used in the hydrogenation of animal and vegetable oils from liquids into solids, ready for use in margarines and soaps.

Extraction and Refining

Nickel derives its name from 'Old Nick', a name for the devil that originated in Germany. Copper miners in the Hartz mountains in Saxony found ores that could not be reduced to workable copper and called them *Kupfer-nickel*, meaning devil's copper. It was later found that the contaminant was a new element—nickel. Nickel often occurs with copper in mineral deposits, together with iron. One of the main nickel minerals is *pentlandite*, a mixed sulphide with iron, $(\text{Ni, Fe})_9\text{S}_8$. It occurs commonly with iron and copper sulphides, such as *chalcopyrite* (CuFeS_2). The



ore mined at Sudbury, Ontario, consists of a mixture of such minerals.

Extracting nickel from its ores is a lengthy process. Methods vary from plant to plant, depending on the exact composition of the ore, the availability of cheap electric power, the type of product desired (finely divided or slab), and so on. In general the nickel-bearing ore is crushed, and its minerals separated from the associated earthy gangue by gravity and magnetic methods or by froth flotation. This yields a mixture mainly of nickel, iron, and copper sulphides. This mixture is then roasted and smelted in several stages, resulting in the removal of much of the sulphur and all the iron. The nickel and copper sulphide matte resulting from smelting is allowed to cool. Crystals of nickel sulphide separate out, together with those of copper sulphide, and a copper-nickel alloy containing traces of precious metals forms as well. Further magnetic separation and flotation processes separate the three constituents.

The nickel may be obtained from the sulphide directly by means of a rather involved electrolytic process. Alternatively, the sulphide can first be converted to nickel oxide and then reduced to impure nickel, before being purified electrolytically. An interesting third method, discovered by Ludwig Mond in the late 1800s, is the *carbonyl* process. In this process the nickel oxide is treated with water gas—a mixture of hydrogen and carbon monoxide. The oxide is reduced, and the nickel combines with the carbon monoxide at about 60°C to form tetracarbonyl nickel $\text{Ni}(\text{CO})_4$, which is volatile. The tetracarbonyl is led away and decomposed into pure nickel pellets.

Above: Some of the essential stages in the extraction and refining of nickel from Sudbury ore. It is a lengthy process because the ore is a mixture of other metals besides nickel. Valuable amounts of silver, gold and metals of the platinum group are recovered as by-products of nickel refining.



Precious Metals

For thousands of years gold and silver have been prized, their scarcity enhancing their superlative qualities. Beautiful to look at, they are durable, slow to tarnish, and very easily worked. Gold in fact is the most ductile and malleable of all metals. It can be beaten into sheet, or *leaf*, so thin as to be transparent: 100 grams of solid gold will yield as much as 100 square metres of gold leaf.

Because of these qualities, silver and gold are *precious* metals. They are also called *noble* metals because they are not readily attacked by atmospheric gases and other common chemicals. They are often described, with copper, as *coinage* metals, because their outstanding durability once made them useful for making coins. But now no major countries use silver or gold in their everyday coinage. The other major group of precious, noble metals contains platinum and the closely related palladium, rhodium, iridium, ruthenium, and osmium. This group is even scarcer than silver and gold.

Silver and Gold

Gold and silver are so chemically unreactive that they can be found native in the ground. Native gold is the most important source of the metal, though a great deal is also obtained as a by-product in processing copper-nickel and lead and zinc ores. Most silver, however, is obtained from sulphide ores, such as *argentite*.

Native gold is very heavy (relative density 19.3) and occurs in placer deposits in stream beds. These were formed as a result of the weathering of gold-bearing surface rocks, and the subsequent action of flowing surface water on the broken-down rock particles. The heavier gold particles tended to settle in the



Top: Panning for gold in southern Africa. In hand panning the miner swirls round a handful of gravel from a stream bed with water. Light earthy material is washed away, and any gold present remains in the pan.

Above: The cyanide tanks at a gold refinery. Cyanide, or rather sodium or potassium cyanide, is used to dissolve gold from the ores in which it occurs.

Right: Gold bars stacked in the vaults of the Bank of England. Each one has a mark which identifies the company that cast it. Gold still forms the basis of most world monetary systems, even though it has long since ceased to be used for coinage.

Left: A great deal of the gold produced by South Africa, the world's biggest producer, is mined deep underground. The gold-bearing ore body is broken up by explosives and by means of pneumatic rock drills.





Above: The photographic industry is a major user of silver. Film is a mixture of silver halide grains suspended in gelatin on a cellulose-acetate base. The grains of silver halide — usually bromide with a little iodide — are sensitive to light. When light strikes the grains they undergo an invisible change which makes them chemically different from unexposed halide grains. When the film is treated with certain organic developing agents, the exposed grains are reduced to metallic silver. The unexposed grains are not affected. They are removed from the film by treatment with a fixing agent such as hypo — sodium thiosulphate. The developed image thus consists of tiny specks of silver.

Top right: The noble metals do not react with body tissue, so they can be used internally in prosthetic devices. This X-ray photograph shows a silver pin inserted through a thigh bone.



stream bed, while the lighter fragments were washed away. Recovering the gold from placer deposits also involves the sorting action of flowing water. Hand panning, or swirling stream gravel and water around in a pan, was the earliest method, used for example by the miners of the gold-rush days in California (1849); the Yukon, Canada (1897); and Australia (1851). Today dredgers and vibrating sluice boxes are used to wash and sort placer deposits.

Gold is also mined underground. It is so precious that it is often worked at tremendous depths. In the Western Deep Levels Mine at Carltonville, South Africa, a depth of more than three kilometres has been reached. South Africa is the world's largest gold-producer, with an output of approximately 570,000 tonnes a year, about 70% of the world total. The gold-bearing ore is usually treated with sodium (or potassium) cyanide solution. The gold reacts with the solution and dissolves, as sodium (or potassium) dicyanoaurate, $\text{Na}[\text{Au}(\text{CN})_2]$. When zinc is added to the solution, the gold is precipitated.

Significant amounts of gold, as well as silver, are obtained by processing the slime that forms at the anode in copper refining (see page 196). The slime is treated with hot concentrated sulphuric acid, which causes other metals present to dissolve, but not the precious ones. The silver is then separated from the gold by electrolysis. In some silver ores, the cyanide process is used to extract the metal, the relevant compound formed being sodium argento cyanide, $\text{Na}[\text{Ag}(\text{CN})_2]$. Extraction of silver and gold forms an important stage in lead and zinc refining.

Both gold and silver conduct heat and electricity well, silver being superior in this respect to every other metal. But copper is generally used instead of silver for heat and electrical applications because it is much

cheaper. Gold is used for long-lasting connections in electrical and electronic components. Dentists use it in alloys for tooth-filling. But its greatest use is in making jewellery. Pure gold is too soft for this purpose, so it is alloyed. Commercial gold may also contain platinum, palladium, silver, copper, nickel, or zinc. The quality of the gold is measured in carats (or karats), a carat being one-twenty-fourth part: 18-carat gold, for example, contains 75% gold.

Similarly, for jewellery and tableware, silver is generally alloyed with copper to make it harder: so-called *sterling* silver contains at least 92.5% silver to 7.5% copper. Much silver tableware is not solid silver but silver plated over a base metal such as brass.

Gold and silver belong, with copper, to Group 1B of the Periodic Table and are transition elements (see page 163). Neither oxidizes in the air, which is why they remain bright. Silver, however, is attacked by sulphurous fumes, which cause a tarnish of black silver sulphide to form over it. Silver resists attack by weak sulphuric and hydrochloric acids, but dissolves in hot concentrated sulphuric acid to form silver sulphate, Ag_2SO_4 , and in nitric acid to form silver nitrate, AgNO_3 . Silver nitrate, also called *lunar caustic*, is a strong oxidizing agent with a caustic action. It forms the starting point for most silver compounds, the most important of which are the silver halides—chloride, bromide, and iodide. Silver halides are essential ingredients in photographic emulsions, for they are very light sensitive. Photographic developing consists of reducing the halide affected by light into metallic silver and dissolving the unaffected halide with a substance, such as sodium thiosulphate. The halides react with sodium thiosulphate to form a complex ion $[\text{Ag}(\text{S}_2\text{O}_3)_2]^{3-}$. Forming complex ions is a characteristic of the transition elements.

The formation by silver and gold of cyanide complexes, as we have seen, is utilized in the extraction of the metals.

In its compounds, silver is generally monovalent, silver(I) (argentous), though it can be divalent, silver(II) (argentic), as in AgF_2 . Gold, too, is generally monovalent, as in gold(I) chloride, AuCl . But it can also be trivalent, as in gold(III) chloride, AuCl_3 .

Gold is not attacked by simple acids; only aqua regia (concentrated hydrochloric and nitric acids) will dissolve it. Evaporation of the solution formed will yield crystals of the complex aurichloric acid, $\text{H}(\text{AuCl}_4)\text{H}_2\text{O}$.

The Platinum Group

One of the finest catalysts for a wide range of chemical reactions is the precious metal platinum. Two processes in which this quality is utilized are the catalytic cracking of petroleum and the manufacture of nitric acid. Platinum is a soft, ductile and very dense metal (relative density 21.5), with exceptional resistance to corrosion; only aqua regia will attack it. Its melting point is high (1769°C). Apart from industrial uses, it is also used for jewellery.

Platinum is one of the commonest of a closely related group of metals, which also include palladium, rhodium, iridium, ruthenium and osmium. They all have a high melting point, excellent resistance to corrosion, and catalytic properties. They are transition elements which occur together in Group 8B of the Periodic Table, the group which also includes iron, cobalt and nickel. After platinum, palladium is the most useful metal of the group. It is cheaper than platinum; it is also lighter and less resistant to corrosion. Its main use is as a catalyst. But it is also used for long-lasting electrical contacts in telephone relays and similar communications devices. It has the interesting property of allowing



An exquisite platinum goblet. Platinum is not widely used for making such large objets d'art because it is too expensive. It is, however, quite commonly used in jewellery.

Platinum is widely used in the chemical industry for its catalytic properties and for its inertness and corrosion resistance. The machine below shows platinum gauze being woven on looms.

hydrogen to diffuse through it at elevated temperatures.

Rhodium is a hard, exceptionally white metal, often used in electroplating. It forms a hard lustrous coating that does not tarnish. It is electroplated on electrical contacts where it guarantees long life. The other major use of the metal is as an alloying element in platinum for use in high-temperature thermocouples.

Iridium is very hard; has a high melting point (2443°C); and is the most corrosion-resistant of the group. It is also the heaviest of all elements (relative density 22.4) after osmium (relative density 22.5). The main use of iridium is as a hardener for platinum. The standard metre and kilogram, for example, are made of platinum-iridium alloy. Naturally-occurring osmium-iridium alloys, known as *osmiridium*, are found in several parts of the world. Ruthenium is used as a hardener for platinum and palladium. Osmium is also very hard and is used to tip pen nibs. But its use is limited because it starts to oxidize at relatively low temperatures.

Whereas the output of many important industrial metals is measured in millions of tonnes, that of metals of the platinum group can be measured in kilograms. Canada, South Africa, and Russia are the largest producers of platinum-group metals, all of which tend to be found together in mineral deposits. Being heavy and corrosion-resistant, platinum and its associated metals are sometimes found native, like gold, in placer deposits in stream beds. Placer deposits in Choco, Colombia, yielded the first specimens of platinum in the 1700s; they are still being worked.

Most platinum-group metals today, however, are recovered as by-products in the refining of copper-nickel-iron sulphide ores, such as those found at Sudbury, Ontario. During processing of the ores the iron is removed and a copper concentrate and nickel concentrate are formed. These concentrates are purified by electrolysis. During electrolysis a slime containing contaminant metals collects at the anode, while only pure copper or nickel is deposited. The slime from electrolysis of the copper concentrate contains significant amounts of silver and gold. That from electrolysis of the nickel concentrate contains recoverable quantities of platinum-group metals, together with some gold.

The first stage in refining of the nickel slime is treatment with aqua regia—a mixture of concentrated hydrochloric and nitric acids. Platinum, palladium, and gold dissolve. Ruthenium, rhodium and iridium do not. The addition of iron(II) sulphate to the solution causes gold to be precipitated. Treatment with ammonia yields a brilliant yellowish-orange precipitate of ammonium chloroplatinate, which is roasted to yield platinum metal. Palladium is also recovered as a precipitate. Care has to be taken to remove all the gold before treatment with ammonia otherwise explosive gold fulminate will be formed.



Tin, Lead and Zinc

These three common metals may not be in the front rank among metals, but they are nevertheless of great importance. Tin and lead are closely related chemically, being in Group 4A of the Periodic Table; zinc on the other hand is in Group 2B. All three metals have reasonable resistance to atmospheric attack and are often used for protective coatings.

Perhaps their greatest importance lies in their use in alloys. Most notable are the alloys of tin and zinc with copper, they being known respectively as *bronze* and *brass* (see page 197). The bronze coins we use contain zinc as well as copper and tin. Lead and tin are the main ingredients of the long-used alloy *pewter*. They also form with antimony the alloy *type metal*. *Solders* used for joining metals are also alloys of tin and lead. Although tin and zinc are comparatively soft and weak metals, their alloys with copper are strong and hard. Lead too, is soft, and like the other metals can be shaped with ease. It is often included in alloys, such as *leaded bronze*, to improve machinability, acting effectively as a lubricant. Its density (relative density 11.3) is much greater than those of tin and zinc (7.3 and 7.1 respectively).

Extraction and Production

Tin occurs in nature primarily as the oxide, SnO_2 , called *cassiterite* or *tinestone*. Cassiterite

Dredging for tin in Malaysia. The Malay Peninsula is the major tin-mining region of the world. Tin ore — cassiterite — occurs in stream and lake gravels. Dredges are used to remove, wash and sort the gravel for the heavy cassiterite particles.

The bubbles on a flotation tank in which zinc sulphide ore — zinc blende — is being separated from associated impurities. The mined ore is first ground fine and then treated with surface-active agents which preferentially wet the impurities present. The fine pure ore particles attach themselves to bubbles of air passing through the tank and collect in the froth at the top, which is floated off.

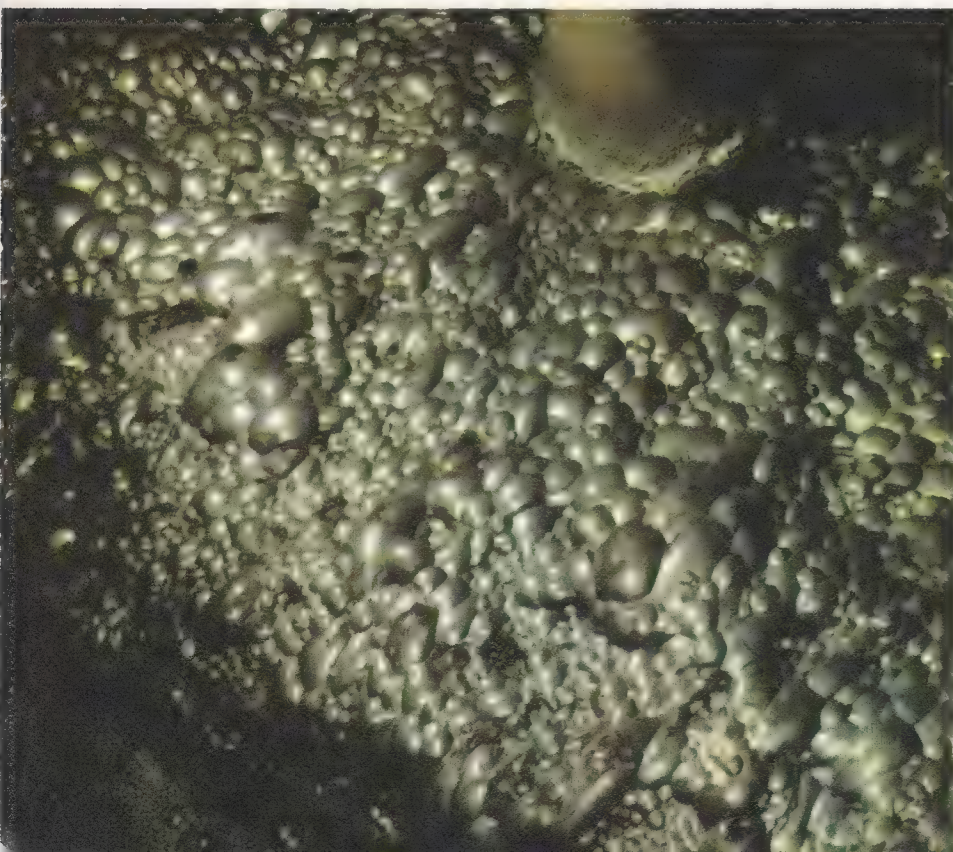


is found in lode deposits underground or in placer deposits in stream beds. It commonly occurs in placers because it is very heavy (relative density about 7)—almost as heavy as iron, in fact. Most of the world's tin comes from placer deposits in south-east Asia, especially Malaysia, which produces about a third of the annual world total of some 210,000 tonnes. Russia and Bolivia also are large tin producers.

Placer deposits are usually smelted directly, while lode deposits are first roasted and then leached with hydrochloric acid to remove major impurities. Smelting of the concentrated ore takes place in a reverberatory furnace. Anthracite is added as a source of carbon, and limestone and fluorspar are added as a flux to assist melting. The carbon in the anthracite combines with the oxygen in the ore, yielding carbon monoxide gas and leaving molten tin. The impure tin resulting may be refined further by heating in a furnace with a sloping hearth or by means of electrolysis.

The lead and zinc ores are sulphides, named *galena* or *lead glance* (PbS), and *zinc blende* or *sphalerite* (ZnS) respectively. The zinc ore is deceptively like the lead ore and, to add to the confusion, they are often found together in mineral deposits. Silver, and sometimes gold, are also often present in the ore body and are extracted as valuable by-products in refining operations. There are vast deposits of lead-zinc ores in many parts of the world. North America has massive deposits in Idaho, Colorado, Missouri and British Columbia. The Broken Hill lead-zinc mines in New South Wales, Australia, are also among the world's largest.

As mined the lead-zinc ore is associated with unwanted earthy material, which is





therefore removed in ore-dressing operations, principally froth flotation. By using different frothing agents, first the galena then the zinc blende can be removed separately as lead and zinc concentrates. Both concentrates are then roasted in air, converting the sulphides to oxides. The oxides are then usually smelted. They are heated in a furnace with coke or anthracite, which combines with the oxygen, leaving the metal.

Smelting practice varies. Lead concentrates can be smelted in a blast furnace in much the same way as iron (see page 191). But zinc cannot be smelted in this way because it volatilizes at a lower temperature (907°C) than that at which reduction will take place. In one operation roasted zinc concentrate is mixed with coal and heated in a retort. The zinc volatilizes and the vapour is led into condensers, where most of it liquefies. It subsequently solidifies to form 98% pure zinc, or *spelter*. Some, zinc, however, condenses as dust. A more recent method reduces roasted mixed lead and zinc concentrates together in a blast furnace. The lead is recovered as liquid at the bottom of the furnace, while the zinc vapour is led away into a shower of molten lead, which absorbs it. On cooling, it forms a layer on top of the lead. Much zinc is also extracted by treating the roasted oxide with sulphuric acid, and electrolysis of the zinc sulphate (ZnSO_4) solution that results. It produces a much purer metal than smelting.

The lead produced in a blast furnace contains numerous impurities, including silver and gold. Their recovery is as much the object of refining as the purification of the lead. The first stage of refining is to melt the impure lead in contact with air in a reverberatory furnace. Some impurities burn away, while

others are removed as surface scum. Zinc is then added to the lead; it absorbs from it any silver and gold, and forms a separate layer.

Chemical Properties

Tin and lead are chemically quite similar and may be either divalent, tin(II) (stannous) or lead(II) (plumbous), or quadrivalent, tin(IV) (stannic) or lead(IV) (plumbic), in compounds. Lead is attacked only slowly by hydrochloric acid, but will dissolve readily in hot concentrated sulphuric acid, forming the lead(II) sulphate, PbSO_4 ; and in nitric acid, forming lead(II) nitrate, $(\text{Pb}(\text{NO}_3)_2)$. In air, lead quickly tarnishes as lead hydroxide and carbonate form, but the surface layer inhibits further corrosion. When heated gently in air, yellow lead oxide, PbO , is formed. A reddish-yellow form of the oxide, called litharge, can be obtained. Roasting litharge in air yields red lead, Pb_3O_4 , a scarlet powder used widely as a paint pigment. Basic lead(II) carbonate, $2\text{PbCO}_3 \cdot \text{Pb}(\text{OH})_2$, or white lead, is also a useful paint pigment, though like most lead compounds it is poisonous. Lead(IV) oxide (PbO_2) is the material used for the positive plate in lead-acid storage batteries (while metallic lead forms the other). The organic compound, tetraethyl lead, is a major additive in petrol, where it improves the octane rating—but at the same time causes pollution.

Tin's most useful characteristic is its resistance to corrosion, which is the reason why it is plated on mild steel to form tinplate. Air and weak acids will not affect it, though dilute mineral acid will attack it to give tin(II) salts, such as $\text{Sn}(\text{NO}_3)_2$. Concentrated acids will usually form tin(IV) salts, such as $\text{Sn}(\text{SO}_4)_2$. Hot alkalis such as caustic soda will attack tin to give a stannate such as Na_2SnO_3 . Tin(IV) oxide (cassiterite) and tin(II) oxide (SnO) are amphoteric. They form salts with acids, and stannates (such as Na_2SnO_3) with alkalis.

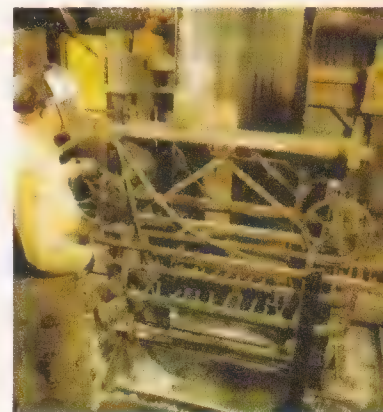
Zinc is widely used to coat steel to protect it from corrosion, a process called *galvanizing*. The zinc coating performs two functions. First, it acts as a barrier against corrosion. Although zinc does slowly corrode in moist air, the surface layer of basic carbonate that forms after a while inhibits further corrosion. Secondly, the zinc protects the steel sacrificially. If the zinc layer is scratched, exposing the steel, the zinc forms the anode of the electrolytic corrosion cell set up and will preferentially be eaten away. Being cathodic, the steel will remain intact (see page 176). In dry batteries zinc forms the outer casing, which acts as the cathode.

Commercial zinc, which contains traces of impurities, dissolves readily in dilute acids, liberating hydrogen and forming the appropriate salt, such as ZnSO_4 . Zinc is invariably divalent in its compounds. Zinc oxide, ZnO , is one of the most important of them, being used as a paint pigment. High-purity zinc oxide is extensively used as a base for pharmaceutical ointments, lotions, and cosmetics.



Crystals of the main lead ore, galena — lead sulphide. Galena, which is also called lead glance, has cubic crystals which have a dull, metallic lustre, resembling that of the parent metal. Galena is very heavy relative density 7.5). Most galena ore bodies also contain valuable traces of silver, and sometimes gold. These metals are valuable by-products of the refining operations.

Galvanized steel strip is usually made by hot dipping. The sheet is first pickled in acid and dipped in a suitable flux before being passed through a bath of molten zinc at a temperature of about 450°C . The zinc reacts with the steel to form a series of alloy layers on the surface. Each successive layer contains a higher proportion of zinc, with the outer layer being almost pure zinc.





Refractory Metals

Of all the metals, tungsten has the highest melting point (3380°C), a quality exploited in most of its applications. One of its most familiar applications is for the filaments of electric-light bulbs. Tungsten is one of several metals exploited for their temperature resistance. Others include molybdenum, which is closely related to tungsten; titanium and zirconium; niobium and tantalum. All these metals are transition metals in groups 4B, 5B or 6B of the Periodic Table. In general they have excellent corrosion resistance, but they tend to oxidize at high temperatures and are usually difficult to fabricate.

Tungsten used to be called *wolfram*, hence its chemical symbol, W. It is immensely strong and hard and is used to impart these properties, as well as temperature resistance, to alloys such as steel. Tungsten carbide, the combination of the metal with carbon, is one of the finest refractory materials. It is used for making high-speed drills, which lose little of their hardness even when very hot. The carbide is made by heating tungsten and carbon black at about 1500°C . It is a common ingredient of *cermets*.

Molybdenum resembles tungsten in many respects, though its melting point is somewhat lower (2620°C). It is also softer and more ductile than tungsten, with which it forms a continuous range of solid solutions. A 50-50

Above: A titanium alloy vacuum chamber manufactured for the European Nuclear Research Organization (CERN). It is a complex assembly of 15 convoluted modules, made by a newly developed blow-forming process similar to that used for shaping glass. This technique is possible with this particular titanium alloy which has superplastic forming characteristics.

tungsten-molybdenum alloy is sometimes used, which combines the higher refractoriness of tungsten with the greater ductility of molybdenum. Molybdenum is also widely used in alloys with steel and non-ferrous metals, where it confers hot strength and corrosion resistance. Molybdenum sulphide is one of its most widely used compounds, acting as a solid lubricant (rather like graphite). Molybdenum occurs naturally as the sulphide in the black mineral molybdenite.

Titanium (melting point 1680°C) is a metal increasingly used for construction, especially in the aircraft industry. It has the desirable properties of lightness combined with high strength and corrosion resistance. Its corrosion resistance depends, like that of aluminium, on the formation of a passive oxide film on the exposed surface. It is easy to fabricate by most methods at room temperature and higher. When molten, it is chemically very active, which makes extraction from its ores very difficult. Zirconium (melting point 1850°C) exhibits much the same properties as titanium but is somewhat softer. It is used in the construction of nuclear reactors, because it has a very low neutron absorption. For this and similar applications traces of the closely related element hafnium must be removed, for hafnium is a strong neutron absorber. The oxide, zirconia, is an excellent high-temperature (2700°C) refractory.

Niobium (melting point 2420°C) and tantalum (melting point 3000°C) occur together in Nature, in the columbite-tantalite series of minerals. (Niobium was once called columbium.) Chemically the two metals are much alike, but some of their physical properties differ. Both metals display excellent corrosion resistance—among acids, tantalum is attacked only by hydrofluoric. Tantalum is very dense, having a relative density of more than 16. This is twice the relative density of niobium.

CERMETS

Composite materials called *cermets* are used in rocket and jet engines and for fabricating hot-forging dies and similar objects. Cermets are combinations of ceramic materials and metals. They combine the highly refractory qualities of ceramics with the ductility, thermal conductivity, and shock resistance of metals.

Most refractory carbides, oxides, and borides, and also certain silicides and sulphides, can be used as the ceramic constituent. Iron, chromium, nickel, cobalt, aluminium, and molybdenum can be used as the metals. Several alloys are suitable, too. Typical ceramic-metal combinations in cermets include zirconium carbide and iron, titanium carbide and cobalt, chromium carbide and nickel, molybdenum boride and nickel, and aluminium oxide and chromium.

The proportion of ceramic to metal varies from cermet to cermet, depending on the exact properties required. On average cermets contain about 80% ceramic and 20% metal. They are generally fabricated by powder metallurgy techniques—the ingredients are mixed together, compacted in a mould and then sintered at high temperature.

Alkali Metals

One of the most reactive groups of elements in Nature are the alkali metals. They are so-called because they react with water to form hydroxides which are strong alkalis. The metals are, in order of increasing complexity, lithium (Li), sodium (Na), potassium (K), rubidium (Rb) and caesium (Cs). There is a sixth alkali metal, francium (Fr), but it is a very unstable radioactive element of which only a few grams ever exist in the Earth's crust at one time. The alkali metals form a very closely knit family, occupying Group 1A of the Periodic Table.

Sodium is by far the most important of the alkali metals, followed by lithium and potassium. Rubidium and caesium are relatively unimportant. They all, however, have much the same physical and chemical characteristics. For example, they are all lustrous metals, so soft that they can be cut with a knife. Their melting points are very low, ranging from 180°C for lithium to only 29°C for caesium. They are very light—lithium, sodium, and potassium being less dense than water. They conduct heat and electricity well, as all metals do. They decompose water vigorously, even violently, liberating hydrogen and forming a hydroxide. They combine very readily with most non-metals such as oxygen, the halogens, and sulphur.

The alkali metals readily lose an electron to form the stable electron configuration of the rare gases. They are completely dissociated in solutions and are usually dissociated in their salts. The ions of the alkali metals are colourless, and so no alkali salt or solution is coloured. With the exception of those of lithium, practically all the salts of the alkali metals are soluble in water. They cannot be precipitated from their solution by any common reagent.

The alkali elements themselves have few uses. Some lithium metal is used in lightweight alloys with magnesium. Sodium metal is used as a coolant in certain types of nuclear reactor; its high conductivity makes it a very effective heat-transfer medium. Sodium vapour is used to fill street lamps, which emit a characteristic yellowish-orange glow. Caesium also is used in vapour form in the atomic clock, the vibration of its atoms acting as a regulator.

Sodium and potassium compounds are by far the most important and most familiar of the alkali metal compounds.

Sodium

One of the most abundant elements, sodium is, like all other alkali metals, too reactive to be

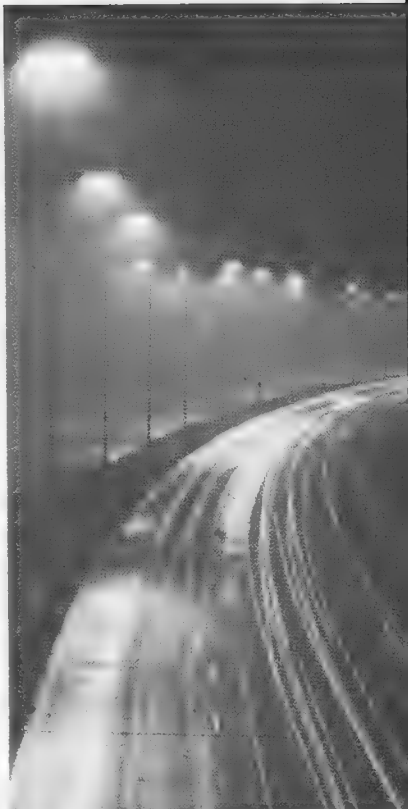
found uncombined in Nature. It occurs widely in the Earth's crust, most notably as *salt* (sodium chloride, NaCl). Massive *rock-salt* deposits occur throughout the world; and the oceans contain nearly 3% sodium chloride. Subterranean brines may contain 25% salt. Among other important sodium minerals are *borax* (disodium tetraborate, $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$); and *Chile saltpetre* (sodium nitrate, NaNO_3). Sodium metal is made by the electrolysis of molten sodium chloride in the Downs Cell (see diagram on page 206). Under electrolysis the salt is split into its component elements, sodium being produced at the cathode, while chlorine is liberated at the anode. Originally sodium was produced by the electrolysis of molten sodium hydroxide, the method used by Sir Humphry Davy when he first isolated sodium in 1807.

Metallic sodium is used as the starting point for the manufacture of numerous sodium compounds, including sodium peroxide, Na_2O_2 , and sodium cyanide, NaCN . Sodium peroxide is produced when sodium burns in air. It is a powerful oxidizing and bleaching agent. Sodium cyanide is important in metallurgy for refining precious metals (see page 200). Large amounts of sodium are also used in the manufacture of tetraethyl lead, used for its anti-knock properties in petrol; sodium alkyl sulphates, used in synthetic detergents; dyestuffs, and numerous other chemicals.

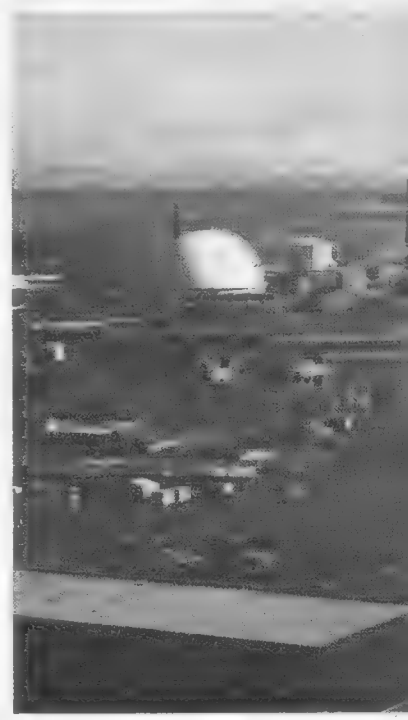
Sodium will react with practically all common elements, the exceptions being boron, carbon, nitrogen, silicon, iron, and nickel. In air sodium quickly oxidizes and becomes covered with a white deposit of sodium hydroxide and carbonate. It has to be stored away from the air, often under kerosene. Sodium combines with chlorine to form sodium chloride, and when hot will attack organic chemicals containing chlorine explosively. Sodium reacts with ammonia and forms sodamide (NaNH_2), which is violently decomposed by water. The metal dissolves in liquid ammonia to give a deep blue solution. It explosively decomposes water and the mineral acids with the formation of sodium hydroxide and the appropriate salt respectively, and with the liberation of hydrogen.

Among sodium's most important manufactured compounds are its hydroxide, carbonate and bicarbonate. Sodium hydroxide, or caustic soda, is made commercially in the Kellner-Solvay cell; chlorine is produced at the same time (see page 231). Caustic soda is a waxy solid that will burn the flesh. It is widely used as a cleansing agent since it emulsifies oil and grease, and it is reacted with fats to form soap. Vast amounts of caustic soda are used in chemical processing—it is used, for example, to dissolve alumina from bauxite, and in the manufacture of rayon.

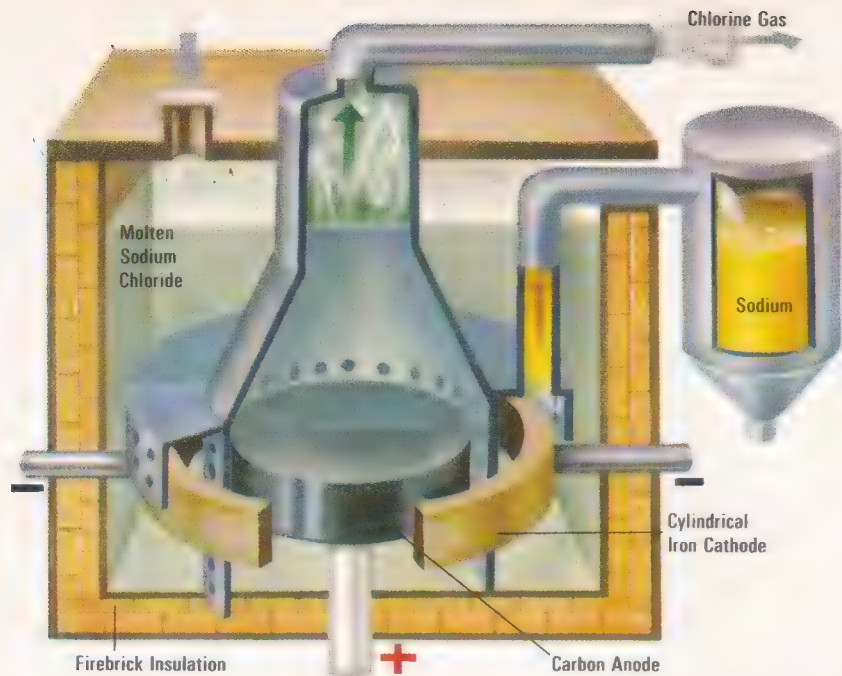
Sodium carbonate is prepared by the ammonia-soda-process, which is diagrammatically outlined on page 173. Carbon dioxide is bubbled through brine saturated with ammonia to form sodium hydrogen car-



Sodium-vapour street lamps emit the vivid orange-yellow glow characteristic of sodium compounds. They are excellent for lighting, but distort the colours of skin, fabrics, and so on.



Metallic sodium in liquid form is used as the coolant in the fast-breeder reactor at Dounreay, Scotland. It has excellent heat transfer characteristics and does not markedly absorb or slow down neutrons.



bonate, better known as sodium bicarbonate, NaHCO_3 , which is roasted to yield sodium carbonate. Hydrated sodium carbonate ($\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$) is familiar as washing soda. The anhydrous form, called soda ash, is used in glass-making. The carbonate is also used as a starting point for making other sodium chemicals. The bicarbonate is familiar as baking soda, and as an antacid used in medicines.

Potassium

Potassium has a very similar chemistry to sodium, with compounds too numerous to be dealt with fully. Potassium is one of the essential elements plants need for proper growth, and for this reason the sulphate (K_2SO_4), chloride (KCl), and nitrate (KNO_3)

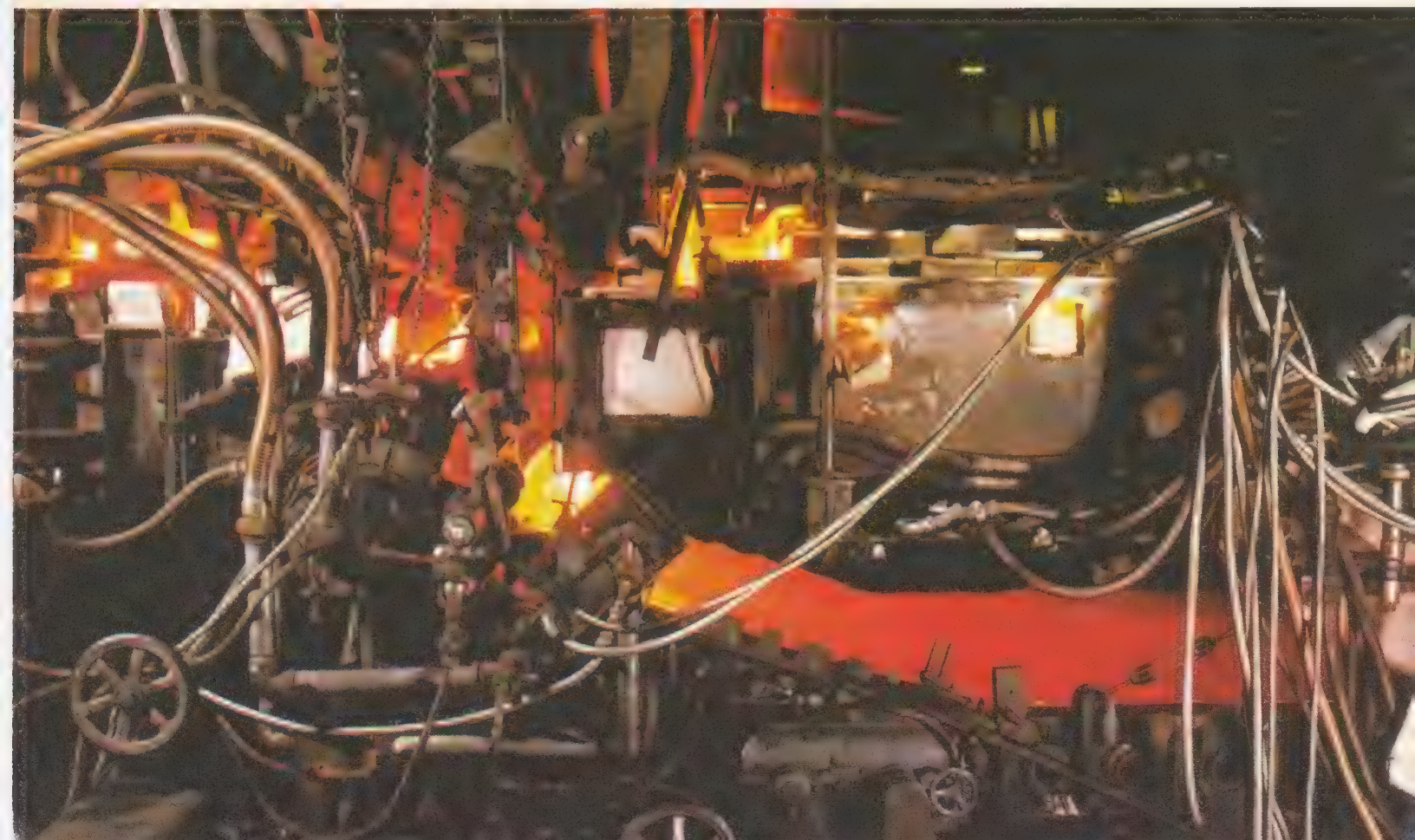
Above: The Downs cell, which is used for the commercial production of sodium metal. In the cell sodium forms at the cathode, while chlorine gas forms at the anode. The liquid sodium rises above the molten sodium chloride because it is less dense.

Below: A sheet of molten glass emerging from a furnace. Soda ash — sodium carbonate — is one of the main ingredients of ordinary soda-lime glass. The other main ingredient besides sand is limestone.

of potassium are used as fertilizers. Potassium nitrate's other important use is as a constituent of gunpowder. Like potassium chlorate (KClO_3), and potassium permanganate (KMnO_4), it is a powerful oxidizing agent.

Potassium chloride is found in the Stassfurt deposits in combination with magnesium chloride in the mineral *carallite*, $\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$. As well as being a fertilizer, the chloride forms the starting point for most potassium salts. The other halides—potassium bromide (KBr) and iodide (KI)—are very useful compounds. The bromide finds use in medicine as a sedative, and in photography. The iodide in solution dissolves iodine. Tincture of iodine, used as an antiseptic in medicine, consists of a solution containing potassium iodide, iodine, and rectified spirit.

Potassium iodide is also used in chemical analysis for estimating oxidizing agents. It is added to the oxidizing agent in the presence of sulphuric acid, and the iodine released is titrated against sodium thiosulphate, $\text{Na}_2\text{S}_2\text{O}_3$. (Sodium thiosulphate is better known as *hypo*, and is used in photographic developing to 'fix' the image by dissolving unchanged silver salts.) Other potassium compounds used in analytical chemistry are the complex potassium hexacyanoferrate(II) (ferrocyanide) $\text{K}_4\text{Fe}(\text{CN})_6 \cdot 3\text{H}_2\text{O}$, and hexacyanoferrate(III) (ferricyanide) $\text{K}_3\text{Fe}(\text{CN})_6$. They are used for identifying the two oxidation states of iron—iron(II) and iron(III). The hexacyanoferrate(II) forms a white precipitate with iron(II) ions and a blue precipitate (Prussian blue) with iron(III) ions. The hexacyanoferrate(III) forms a blue precipitate (Turnbull's blue) with iron(II) ions and a brown solution with iron(III) ions.





Alkaline Earth Metals

This family of metals, in Group 2A of the Periodic Table, comprises beryllium, magnesium, calcium, barium, strontium and radium (which is radioactive). The most important of these metals by far are calcium and magnesium, whose compounds occur abundantly in the Earth's crust and are exploited on a large scale in industry. This family lies next to the alkali metals in the Periodic Table. And the chemistry of the two groups is quite similar, though the alkaline earths are divalent, while the alkali metals are monovalent. For example, they both attack water, liberating hydrogen; but with the alkaline-earth metals, the reaction is much less vigorous. In their compounds they are invariably ionized, and their ions are colourless. Their hydroxides are basic; and their sulphides are soluble in water. However, alkaline-earth compounds are more readily decomposed than those of the alkali metals; their hydroxides are weaker bases; and many of them are insoluble in water, unlike most alkali-metal compounds.

The alkaline-earth metals are grey in colour and are moderately hard. They have relatively high melting points, ranging from 1280°C for beryllium to 850°C for calcium. Like all metals they conduct heat and electricity well. Industrially, the most important of the metals is magnesium. It is a very lightweight metal (relative density 2.7). It is alloyed with aluminium, zinc, and manganese to make lightweight alloys for use in aircraft. These alloys are readily shaped by

normal methods such as forging, casting and machining. Indeed magnesium is the easiest of all metals to machine.

Beryllium, which is obtained primarily from the oxide mineral *beryl* ($3\text{BeO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$), has also begun to have metallurgical importance. It is only slightly heavier than magnesium but has greater mechanical strength and a much higher melting point. Its oxide (beryllia) is an important high-temperature refractory, like magnesium oxide (magnesia). Few of its other compounds have any importance.

Magnesium

In Nature magnesium is never found uncombined, for, like all the alkaline earths, it is too reactive. Among the minerals containing magnesium are *magnesite*, MgCO_3 ; *dolomite*, $\text{CaCO}_3 \cdot \text{MgCO}_3$; *kieserite*, $\text{MgSO}_4 \cdot \text{H}_2\text{O}$; *carrollite*, $\text{MgCl}_2 \cdot \text{KCl} \cdot 6\text{H}_2\text{O}$; and many silicate minerals, including *talc* and *asbestos*. Seawater contains an abundance of magnesium in the form of soluble chloride, and extraction plants now process seawater to obtain magnesium metal. In the extraction process, the water is first treated with calcium hydroxide, causing magnesium hydroxide to be precipitated. The hydroxide is then reacted with hydrochloric acid to form the chloride, which is then dried. Magnesium metal is obtained by electrolysis of the molten chloride, chlorine also being produced.

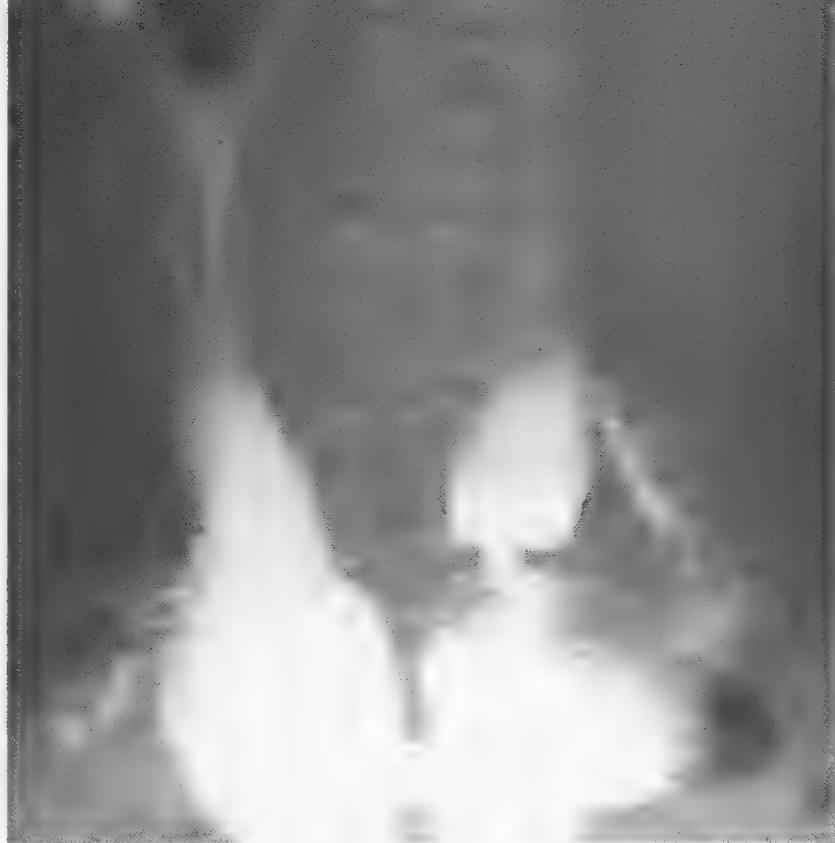
Apart from its structural uses, magnesium metal is used in pyrotechnic devices such as incendiaries and flares, for it burns brilliantly when set alight. Burning yields a pure white smoke of magnesium oxide, MgO , whose melting point is 2850°C. Some magnesium nitride, Mg_3N_2 , is also formed. Magnesium shows little reaction with water at room temperature, because a film of the highly insoluble hydroxide quickly covers it, thus preventing further attack.

The hydroxide is the familiar household chemical, *milk of magnesia*. Being quite strongly alkaline, it is useful as an antacid for stomach disorders. Very dilute acids will dissolve magnesium readily, liberating hydrogen and forming the appropriate salt, such as magnesium sulphate, MgSO_4 . The widely used

Above: Much of the colour in firework displays is provided by compounds of the alkaline-earth metals strontium and barium. Strontium is responsible for the vivid crimsons, barium for the ethereal greens.

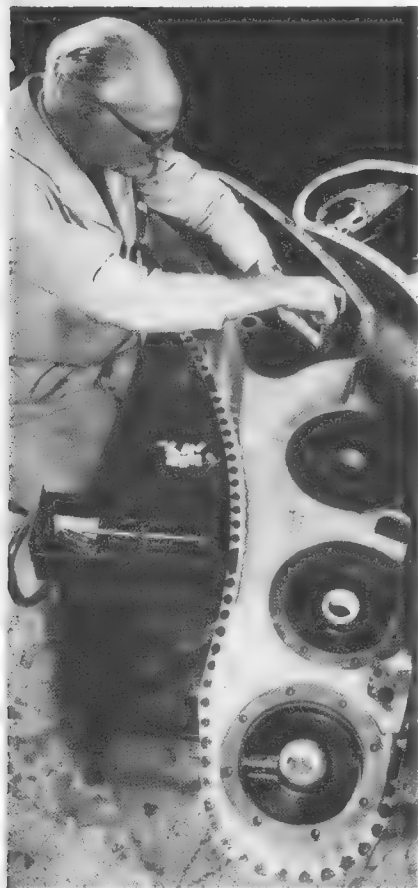
Below: Stalagmites and stalactites adorn this natural grotto. They are formed by lime-laden waters dripping from the roof of the cave. Each drip deposits minute specks of calcium carbonate as it leaves the roof and as it hits the ground. Over the years the specks build up on the roof to form stalactites, and on the ground to form stalagmites.





Above: An X-ray photograph of the human digestive system. Normally this would not be visible on an X-ray. It shows up here because the patient has had a 'barium meal' — a liquid containing barium sulphate. This mineral is highly opaque to X-rays.

Below: A magnesium alloy casting used on the RB-211 turbofan engine which powers the Lockheed Tristar Airbus.



purgative *Epsom salts* consists of hydrated magnesium sulphate, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$. Magnesium sulphate has numerous other uses, being used in the manufacture of paints, paper, cement and fertilizers. Magnesium carbonate, MgCO_3 , is used to make refractory bricks for furnace linings. The basic carbonate is a valuable filler for paints and paper and a bulking agent in pharmaceutical powders.

Calcium

The fifth most abundant of all the elements, calcium comprises nearly 4% of the Earth's crust. It is most commonly found as the carbonate, CaCO_3 , in massive sedimentary rocks such as *limestone* and *chalk*. These deposits were formed hundreds of millions of years ago from the remains of marine organisms, such as coral and shellfish, which extracted calcium from the ancient seas to build up their shells. The most important of the other naturally-occurring calcium minerals are the double carbonate with magnesium, *dolomite*; the sulphate, *gypsum*, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, and *anhydrite*, CaSO_4 ; the fluoride, *fluorite*, CaF_2 ; and the mixed fluoride and phosphate, *apatite*, $3\text{Ca}_3(\text{PO}_4)_2\text{CaF}_2$. Calcium phosphate itself, $\text{Ca}_3(\text{PO}_4)_2$, is the main constituent of bones.

These naturally occurring compounds have endless uses. Vast amounts of limestone are used in iron and steel refining, in glass making, and many other major industrial processes. Much limestone is burned in lime kilns to make *quicklime* (calcium oxide, CaO). A white powder, quicklime becomes incandescent at high temperatures emitting a dazzling white light—*limelight*. It was once used in theatrical spotlights, hence the term 'in the limelight'.

A great deal of heat is given out when water is added to quicklime to produce *slaked lime*, calcium hydroxide, $\text{Ca}(\text{OH})_2$. Slaked lime forms the basis of mortar and building plasters. It is used in agriculture as a fertilizer

and a soil conditioner for neutralizing acid soils. A suspension of slaked lime in water, called milk of lime, is a cheap, effective industrial alkali widely used for neutralizing acids. Slaked lime absorbs chlorine to a significant degree, forming *bleaching powder*, a widely used industrial bleaching agent.

Gypsum is used to make *plaster of Paris*, from which plaster casts are made. First the gypsum is heated to drive off some of its water of crystallization, forming $2\text{CaSO}_4 \cdot \text{H}_2\text{O}$. When this is mixed with water, it can be moulded into shape. But it quickly sets hard as gypsum reforms.

Calcium metal can be made by the electrolysis of calcium chloride, large amounts of which are available as a by-product of the ammonia-soda process for sodium-carbonate manufacture (see page 173). It is a soft metal which is attacked by damp air and which dissolves readily in water, forming the hydroxide and liberating hydrogen. It dissolves vigorously in dilute acids. It will combine when heated with nitrogen, chlorine, sulphur, and hydrogen. The hydride, CaH_2 , forms a convenient portable source of hydrogen, which is released when water is added to it.

Calcium carbide, CaC_2 , made by heating quicklime and coke, is one of calcium's most interesting compounds, for it can be used to make organic compounds. It reacts vigorously with water, for example, to yield acetylene gas, C_2H_2 . When heated strongly with nitrogen, it forms calcium cyanamide, which is an important fertilizer and also a starting point for the synthesis of many useful chemical products, including melamine resins.

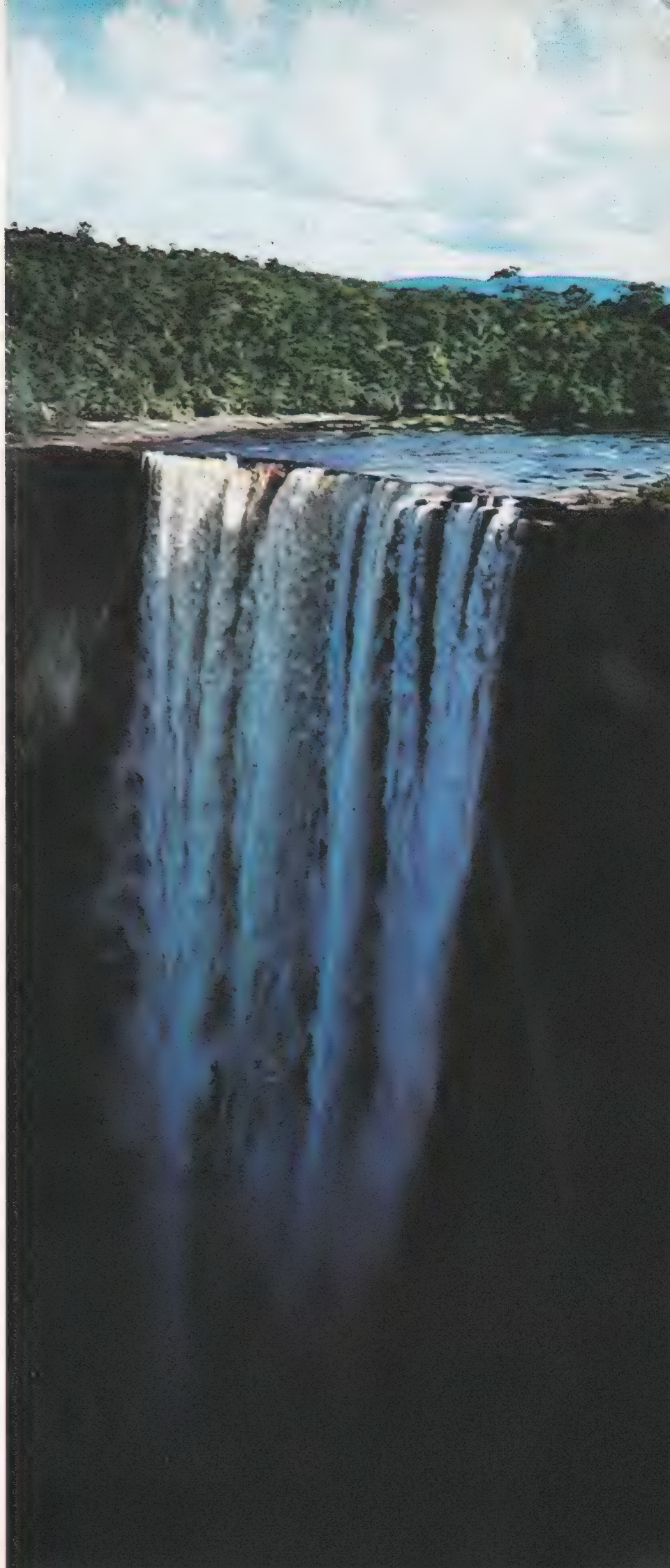
Strontium and Barium

Although not very important, these alkaline earths do have one or two useful compounds. Strontium chlorate, $\text{Sr}(\text{ClO}_3)_2$, and nitrate, $\text{Sr}(\text{NO}_3)_2$, are incorporated in fireworks, flares, and other pyrotechnic devices, where they impart a vivid crimson colour. Barium nitrate, $\text{Ba}(\text{NO}_3)_2$, is similarly used, but it imparts an apple-green colour. Strontium hydroxide, $\text{Sr}(\text{OH})_2$, is often used in sugar refining to extract sugar from solution. It forms a so-called *saccharate* with the sugar, which can be regenerated by the action of carbon dioxide.

Barium sulphate, BaSO_4 , which occurs naturally as *barytes*, or *heavy spar*, is the white substance given as a barium meal to patients in hospital having stomach and intestinal X-rays taken. The mineral is particularly opaque to X-rays, and causes the inner organs to show up on the X-ray film. Barium sulphate is practically insoluble in water as is the carbonate, which occurs naturally as *witherite*. The carbonate, together with all soluble compounds of barium, is poisonous. Other major uses for barite are as a paint filler and pigment (with zinc sulphate, in lithopone). It is also incorporated in the mud used in petroleum drilling, where its high density (relative density 4.5) proves valuable.

Air, Fire and Water

Water is the chemical compound that is essential to life on Earth. But it also provides some of the world's most dramatic and beautiful sights, such as this waterfall.





The Atmosphere

The Earth is enveloped by a layer of gases which we call the atmosphere. This layer is effectively only a few hundred kilometres thick. If the Earth were an apple then the atmosphere would be no thicker than the peel. Yet the atmosphere is of the most profound importance. By providing oxygen for respiration it allows an abundance of life to exist on Earth. It absorbs harmful radiation from the Sun and acts as a blanket to equalize day-time and night-time temperatures by trapping the Sun's day-time heat.

Oxygen makes up only about 21 per cent by volume of the atmosphere. Most of the remainder is nitrogen (78%). There is also argon (0.93%), carbon dioxide (0.03%), neon (0.002%), and traces of many other gases, including sulphur dioxide, carbon monoxide and nitrogen oxides. The latter are more prevalent in industrial areas and are the main sources of atmospheric pollution. Water vapour, too, is always present in the atmosphere in varying quantities.

The Evolution of the Atmosphere

The composition of the atmosphere has changed radically since the Earth was formed. The primeval atmosphere is thought to have contained an abundance of methane (CH_4), ammonia (NH_3), carbon dioxide (CO_2) and hydrogen, as well as nitrogen and water vapour. It is unlikely that there was very much, if any, free oxygen. When life began on Earth some 3500 million years ago, the first organisms must have been able to live without oxygen, just as yeasts and other organisms that produce fermentation do today. Eventually, organisms evolved that produced oxygen as part of their life processes. Living in the sea they escaped the deadly

ultra-violet radiation in which the surface of the planet was bathed.

The oxygen produced in the sea gradually found its way into the atmosphere. In addition, radiation broke down atmospheric water vapour into hydrogen and oxygen. Being such a light gas, most of the hydrogen escaped into space. But the heavier oxygen remained behind, trapped by the Earth's gravity.

As oxygen slowly began to build up in the atmosphere, ultra-violet radiation from the Sun changed it into a highly reactive unstable substance called *ozone*. An oxygen molecule consists of two atoms of oxygen (O_2), while ozone (O_3) has three atoms.

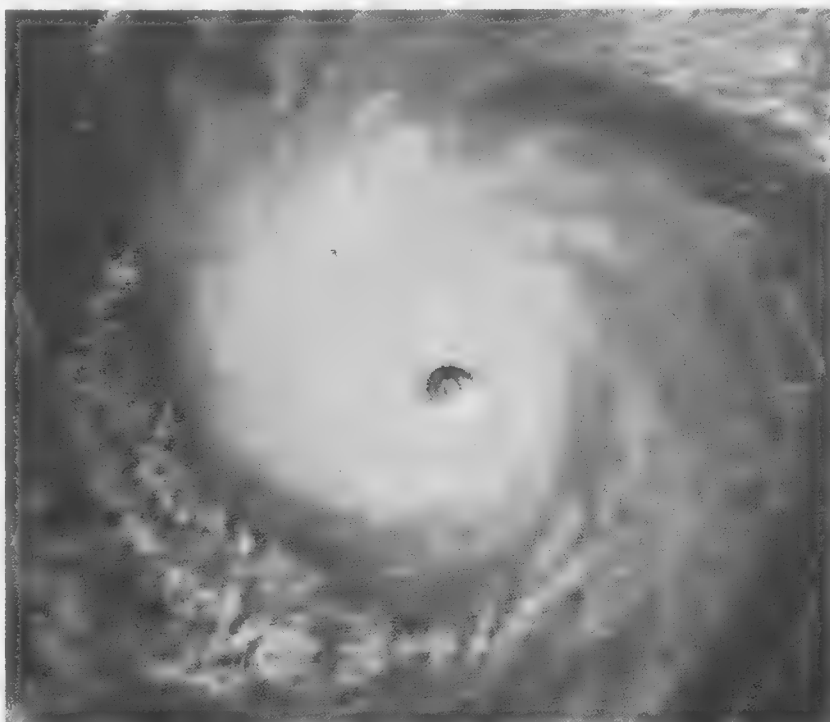
As the layer of ozone above the Earth increased in density, more and more of the ultra-violet radiation from the Sun was cut off from the Earth's surface. More oxygen therefore appeared at ground level (ozone is too unstable to remain free in great quantities in the normal atmosphere). Hence oxygen-breathing organisms were able to develop. Plants were the first to establish themselves firmly as users of the new environment because they could use the large amounts of carbon dioxide in the atmosphere as an energy source. And in doing so they increased the oxygen content of the air by releasing it. The process in which plants take in carbon dioxide and release oxygen is called *photosynthesis*.

The ozone barrier is one of the main atmospheric protectors of life on Earth. The maintenance of this barrier has recently provoked a major controversy over the development of supersonic aircraft, such as *Concorde*. Aircraft like this are expected to come into increasing use over the next decade.

Supersonic aircraft are built to fly at high speed in the stratosphere. And it is the height that they reach for long periods that is worrying some scientists. They suggest that, as

Above: When dark, towering cumulonimbus clouds like this build up, a thunderstorm is on the way. This particular type of cumulonimbus is called anvil-head because of its shape.

This photograph of hurricane Ava over the eastern Pacific was taken by the polar-orbiting satellite NOAA-2, a weather satellite launched on behalf of the National Oceanic and Atmospheric Administration of the US.





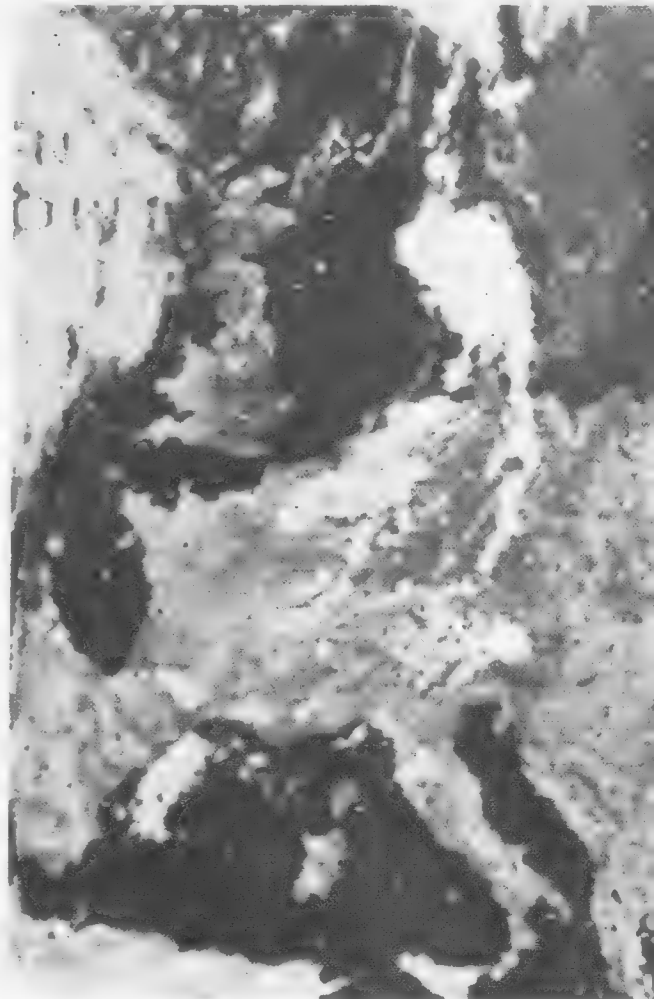
surface of the planet. In fact, half of the atmosphere's total mass lies within 5.5 kilometres of sea level. The pressure of the atmosphere at sea level is about one kilogram per square centimetre, termed *one atmosphere*. The pressure drops markedly with height above sea level. At 10,000 metres (little more than the height of Everest) the pressure is less than one-third of an atmosphere. Thereafter, the pressure falls even more rapidly until at a height of about 800 kilometres there are only a few gas molecules remaining, mainly of hydrogen and helium. The atmosphere gradually merges with space.

Layers of Air

The atmosphere can be divided into five main regions: the *troposphere* (the lowest layer), the *stratosphere*, the *mesosphere*, the *ionosphere* and the *exosphere*.

The troposphere is the part of the atmosphere in which we live and to which weather is confined. Temperature decreases steadily with height in this region, falling to a freezing -55°C at the *tropopause*, a thin boundary layer marking the top of the troposphere. The height of the tropopause varies from 16 kilometres over the equator to 8 kilometres over the polar regions. Icy, high-speed winds called *jet streams* blow in thin ribbons around the world at this height. Their speed can exceed 240 kilometres per hour.

Except on short flights, airliners climb



these aircraft become more common, the ozone layer in the stratosphere will gradually be broken down, removing the Earth's protection against ultra-violet radiation. This, they argue, will lead to an increased incidence of such conditions as skin cancer. Passengers travelling in such aircraft could be subjected to an abnormal level of cosmic rays, which normally never penetrate the atmosphere. Supporters of the new technology say that the ozone layer is self-generating and will not be damaged by high-flying aircraft. The risks from cosmic rays, they say, are negligible.

The Pressure of the Air

The Earth's gravity not only prevents the gases of the atmosphere from escaping into space; it also compresses them against the

Above: Radiosondes carry instruments high into the atmosphere to measure temperature, pressure and humidity. They are tracked by radar. The radar reflector hangs beneath the balloon. The instrument package is at the bottom. Readings are radioed back to ground control.

Right: A Nimbus weather satellite picture of Europe. It shows the skies free of cloud practically everywhere. Only over Ireland has cloud built up.

through the tropopause into the calmer air of the stratosphere. Wind speeds decrease with height in the stratosphere, but the temperature *increases*. In the short space of 25 kilometres it rises to around freezing point. This warming effect is due to the action of ultra-violet rays from the Sun. As ultra-violet radiation changes oxygen into ozone, heat is produced.

The Upper Atmosphere

Above the ozone layer lies the mesosphere in which the temperature falls to -70°C at its boundary with the ionosphere (about 80 kilometres above the Earth).

The ionosphere is so called because the atoms of gas there are *ionized* (turned into electrically charged atoms, or *ions*) by the passage of ultra-violet rays, X-rays, and streams of atomic particles from space. Heat is produced in the process and the temperature in the ionosphere consequently rises with height to more than $20,000^{\circ}\text{C}$. The ionosphere is vital to life on Earth. It is at this level that most of the harmful radiation from space is absorbed. The upper levels of the ionosphere also cut down the amount of infra-red ('heat') radiation reaching the Earth's surface. The ionosphere is also important in radio communications because it contains layers which are able to reflect certain radio waves. Before the advent of communications satellites it was these reflective layers alone that enabled radio transmissions to be picked up around the world.

The ionosphere is usually divided into three layers: the D-region above 80 kilometres; the E-region, or *Heavyside-Kenelly layer*, above 130 kilometres; and the F-region, or *Appleton layer*, above 160 kilometres. (The F-region is sometimes divided into the F1 and F2 regions.)

The upper ionosphere contains a high proportion of nitrogen, but very little oxygen. Instead, a great deal of ozone is found. Nearer to the Earth's surface, the E-region contains more nitrogen and more oxygen, but the proportion of ozone is correspondingly less.

The actual chemical content of the ionosphere changes from day to day, varying with the radiation bombardment from space. The number of free ions and electrons in the ionosphere changes with the time of day as well. At night, when the Sun's rays are not falling on the ionosphere, the charged particles tend to recombine in the lower parts of the layer. But at higher levels the atmosphere remains substantially ionized because the lower density of ions decreases the chance of collisions with free electrons and with each other.

Above 500 kilometres lies the exosphere, the tenuous outermost layer of the atmosphere which merges imperceptibly with space. It consists mainly of hydrogen and helium, the two lightest gases, with the proportion of hydrogen increasing with distance from the Earth. Traces of the exosphere have been found as far as 8000 kilometres out in space.

Right: Diagram showing the structure of the atmosphere, the change in temperature, pressure and composition with height, and the passage of electromagnetic radiation.

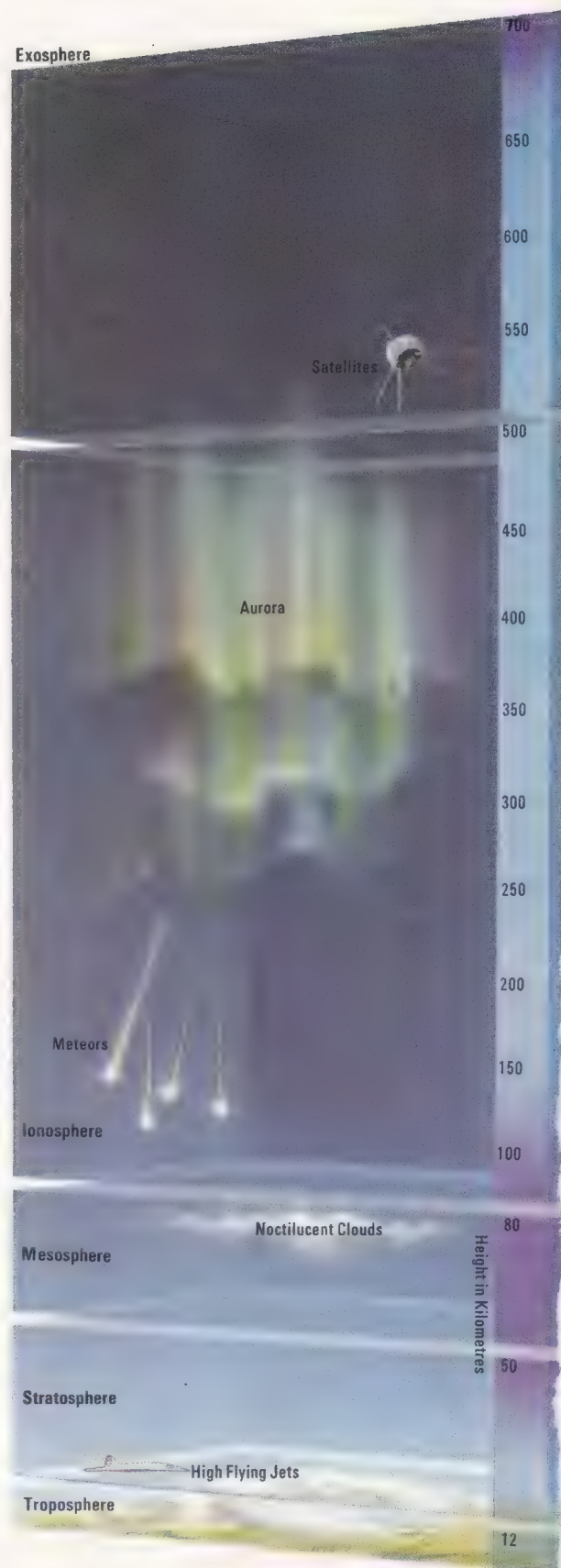
Structure: The atmosphere may be divided into the troposphere, stratosphere, mesosphere, ionosphere and exosphere.

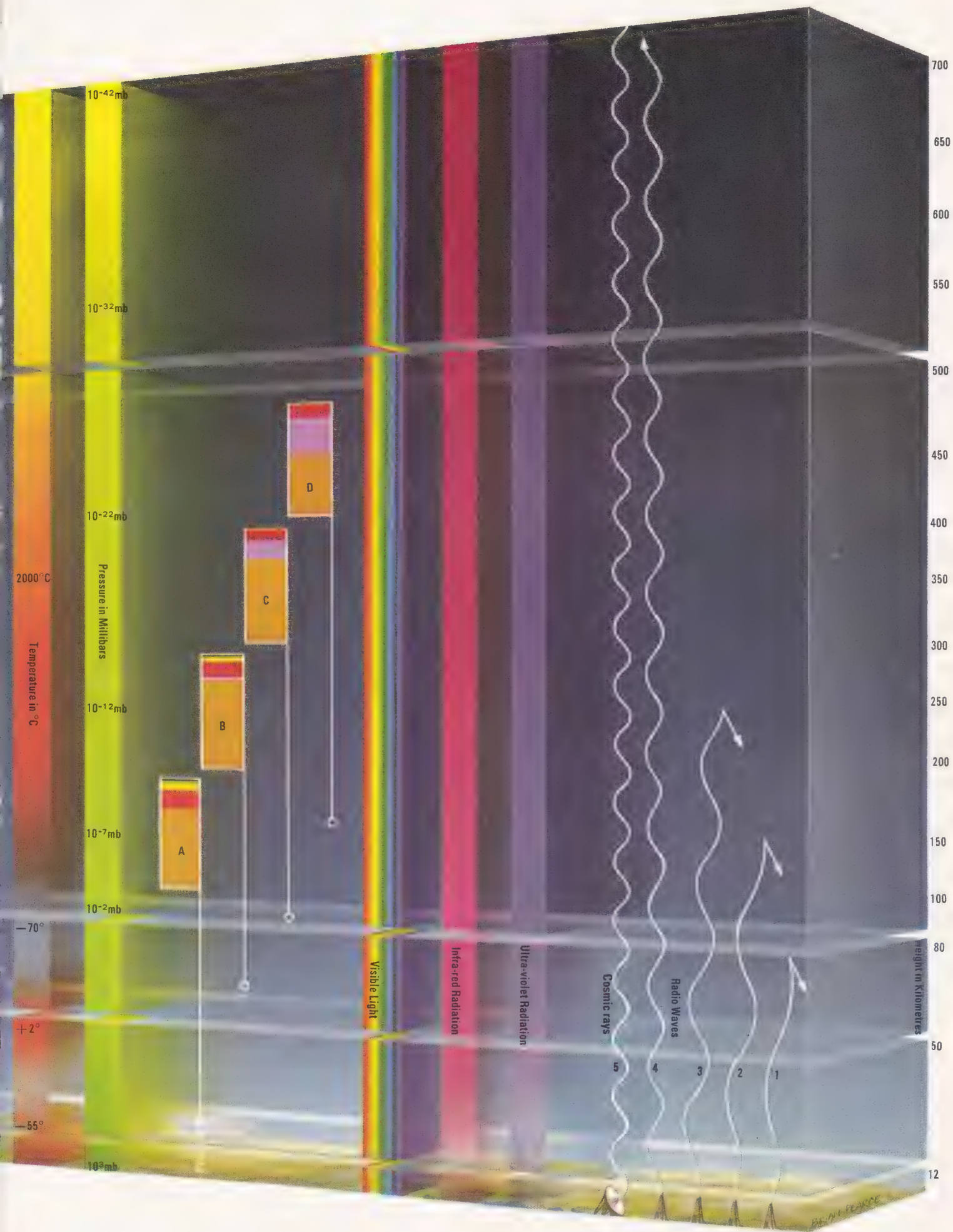
Temperature decreases with altitude in the troposphere but increases in the stratosphere. It falls again in the mesosphere but increases with altitude beyond the boundary with the ionosphere.

Pressure decreases rapidly with altitude. Over 90% of the total air mass is contained within the troposphere and over 50% within 5 kilometres of the Earth's surface.

Composition: The composition of the atmosphere varies with height as shown in panels A, B, C, and D, where orange represents nitrogen, red oxygen, purple ozone, yellow rare gases, green water vapour, and deep blue carbon dioxide.

Electromagnetic Radiation
The atmosphere shields the Earth from much of the Sun's infra-red radiation and the ozone layer absorbs most of the ultra-violet radiation but the air is transparent to the wavelengths of visible light and cosmic rays. Long-wave (1), medium wave (2) and short-wave (3) radio transmissions are reflected at various levels in the atmosphere, but very high frequency (VHF) radio transmissions (4) pass into space.





Nitrogen

Nitrogen is a colourless, odourless gas that makes up four fifths of the air we breathe. It does not burn and hardly dissolves in water at all. Nitrogen molecules in the air contain two atoms. These diatomic molecules are extraordinarily stable. The gas has to be heated before it will react. And even when heat is applied, it reacts with oxygen only very slowly. Experiments show that below 1500°C , the reaction is negligible. Even at 3000°C only about five per cent combination is achieved. This stability is fortunate; without it all the nitrogen and oxygen in the atmosphere would have combined long ago.

Nitrogen in Nature

Nitrogen is found in all organisms and is a vital part of proteins and other chemicals in the body. Air-breathing animals cannot use nitrogen directly from the air. They obtain it in their food. Some plants, however, have the ability to 'fix' nitrogen, combining it with other chemicals in complicated chemical reactions. Other plants absorb it in chemical form directly from the ground. When animals and plants die and rot, their nitrogen content either returns to the ground in chemical form or is given off into the atmosphere, usually as ammonia (NH_3).

As world demand for food has risen, it has been found that there is not enough readily-available nitrogen in the soil, so the natural levels of the element are supplemented by the use of nitrogen-containing fertilizers. Fertilizers such as calcium cyanamide (CaNCN), made by passing nitrogen over calcium carbide (CaC_2) at about 1000°C , are broken down in the soil into nitrates and calcium products, which can then be taken up by plants.

Nitrogen in Industry

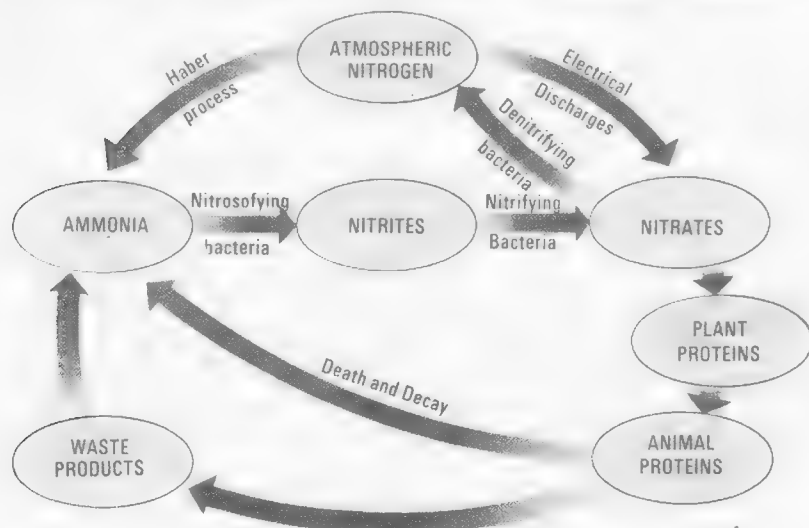
Nitrogen is also found in naturally occurring chemicals such as Chile saltpetre, a nitrate



Below: The natural nitrogen cycle. Nitrogen is essential to plant and animal life, being present in the protein of body tissues. Plants acquire their nitrogen through the absorption of nitrates from the soil. The nitrates are replenished naturally as a result of electrical discharges in the atmosphere, which result in the production of nitric acid. The rain washes the nitric acid into the soil, where it forms nitrates. Nitrates are also formed by the oxidation of ammonia produced by the rotting bodies of animals and plants. Bacteria in the soil bring about the oxidation. Denitrifying bacteria convert some nitrates into free nitrogen.

which was at one time the main industrial source of nitrogen gas. Now nitrogen is extracted from the air. Air is a mixture of nitrogen, oxygen and a small proportion of other gases. Nitrogen boils at -196°C , about 13 degrees below the boiling point of oxygen. This difference is used industrially to separate the two gases from liquid air. Gaseous air is first cleaned. Dust, carbon dioxide and water vapour are removed. Then the air is cooled and compressed until liquid air is formed. Nitrogen is then allowed to boil off, leaving the liquid oxygen behind. The nitrogen still contains some impurities, such as argon. These can be removed by distillation to give pure nitrogen. Nitrogen gas can be made in the laboratory by a variety of methods, but it is usual to heat a nitrogen-containing chemical that breaks down fairly easily. For example, if ammonium nitrite (NH_4NO_2) is warmed, it decomposes to give pure nitrogen and water.

Nitrogen is extensively used in industry. In gaseous form, it is used as a filling for light bulbs because its inertness protects the delicate filament, which would burn away very quickly if it were exposed to the air. It is also used in some forms of welding to protect metals which would otherwise oxidize at the high temperatures employed. The low temperature and easy availability of liquid nitrogen enable it to be used in the repair of oil pipeline leaks; the pipe is frozen while the repair is carried out. Liquid nitrogen is also used in civil engineering where waterlogged ground is to be excavated. The ground is frozen to prevent water seeping into the diggings. This method of excavation has been used in Holland in the construction of underground railways in low-lying ground.





Liquid nitrogen has some interesting industrial uses. Here it is being used to freeze the contents of a section of oil pipeline. Part of the section can then be removed for repair or replacement. Such a procedure makes repair of a pipe a simple operation. It avoids having to drain the pipeline, a tedious and time-consuming operation.

Ammonia

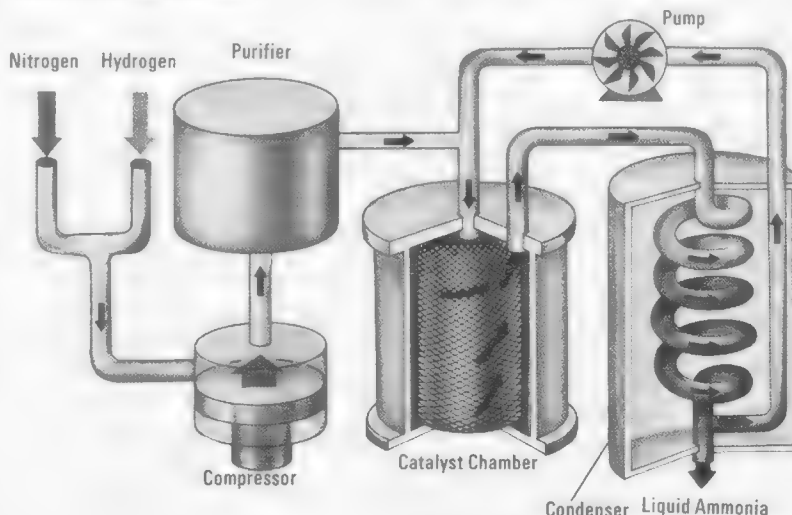
Most of the nitrogen produced industrially is used in the manufacture of ammonia. Ammonia used to be made from coal, but in the early years of this century it was found that if nitrogen and hydrogen are heated together at high pressure, they combine to give ammonia. This process, known as the *Haber process*, has largely superseded other methods of manufacturing ammonia. High temperatures (500°C) and pressures (1000 atmospheres) are needed in this process because of the stability, or inertness, of the nitrogen molecule.

The inertness of the molecule is explained by the structure of the electron shells around the nucleus. Each nitrogen atom has 7 electrons, two in the shell nearest to the nucleus and five in the next shell. The five electrons are arranged as one pair and three single electrons. When two atoms of nitrogen come together to form a molecule, the three single electrons in each atom are shared with the other atom. This means that the combined outer shell of the molecule has five pairs of electrons, three of which are shared. It is this triple sharing of electrons, or triple bonding, which makes the nitrogen molecule so stable. A great deal of energy has to be used to break the bonds and this accounts for the high temperatures and pressures used in the manufacture of ammonia.

Industrially-produced ammonia is mostly used for the commercial production of nitrogen-containing fertilizers, nitric acid (HNO_3), and explosives. But large amounts are also used in the manufacture of modern dyes and in the plastics industry for the manufacture of nylon.

In the laboratory ammonia is not made by the direct combination of nitrogen and hydro-

A diagram representing the Haber process for the manufacture of ammonia from nitrogen and hydrogen. Three volumes of hydrogen and two volumes of nitrogen will combine to form two volumes of ammonia, the reaction being reversible. This reaction takes place at a reasonable rate at a temperature of about 500°C , under a pressure of about 1000 atmospheres, and in the presence of an iron catalyst. Only part of the reacting gases combine as they pass through the catalyst chamber. The gas leaving the chamber is cooled, whereupon ammonia condenses. The uncombined nitrogen and ammonia are recirculated into the catalyst chamber.



gen. The usual method is to heat an ammonium compound such as ammonium chloride (NH_4Cl) with an alkali such as caustic soda (NaOH). In contrast to nitrogen, ammonia is extremely soluble in water. At normal temperatures and pressures one volume of water will absorb about 1200 volumes of the gas.

The Oxides of Nitrogen

Ammonia is not the only important nitrogen-containing compound. Nitrogen forms three oxides which are very common in industry. Dinitrogen oxide, or nitrous oxide (N_2O), is often called laughing gas. Mixed with oxygen it is used in hospitals as a general anaesthetic, but small amounts of the gas tend to cause hysteria and that is how it got its name. It was first discovered, in 1798, by Humphry Davy. Shortly after that it became fashionable to hold laughing gas parties, at which people reached a state similar to drunkenness.

Nitrogen oxide (NO), sometimes known as nitric oxide, is a gas which rapidly reacts with oxygen to give the third oxide, nitrogen dioxide (NO_2). Because it reacts so readily, the smell of nitrogen oxide is unknown.

At normal temperatures nitrogen dioxide is a brown, evil-smelling gas. But at low temperatures it liquefies into a very poisonous yellow liquid. In the liquid form, pairs of dioxide molecules (NO_2) associate to form the tetroxide (N_2O_4). If the tetroxide is warmed, the pairs of molecules separate to reform the dioxide. The process is complete at about 150°C . The dark brown of the dioxide is at its deepest at this temperature. But if heating is continued up to about 600°C , the colour fades and dies away completely. This is due to the break-up of the dioxide molecules into nitrogen oxide and oxygen. This break-up, known as *thermal dissociation*, is reversed as the temperature falls, the brown colour of the dioxide reappearing as the molecules reform with cooling.

Nitriding

Metals combine with nitrogen on heating, forming substance called nitrides. This process is used industrially for hardening the surface of steel and is called *nitriding*.



Above: Oxyacetylene welding. Oxygen and acetylene are fed to the welding torch to produce a flame burning at about 3500°C.

Oxygen

Oxygen is the commonest element on Earth. Nearly all rocks and clays in the Earth's crust contain a high proportion of it in chemical combination, as do many minerals. The oceans are composed of about 86 per cent by weight of oxygen. It is also an essential constituent of all living things; more than 70 per cent by weight of the human body is oxygen in chemical combination.

Oxygen is a colourless, odourless gas that makes up about 21 per cent of the atmosphere. The proportion remains fairly constant because oxygen consumed during respiration and combustion is continually replaced by the photosynthetic processes of plants. Photosynthesis is the process by which plants form organic compounds from carbon dioxide (CO_2) and water (H_2O) using energy in the Sun's rays. Respiration is the chemical process by which animals use oxygen to break down food into energy. Photosynthesis and respiration are coupled by the constant flow through the biosphere of the raw materials for their reactions. Respiration uses up oxygen and produces carbon dioxide; photosynthesis uses up carbon dioxide and produces oxygen.

The Manufacture of Oxygen

Oxygen is manufactured by separation from liquid air in a process known as *fractional*

distillation. Air is compressed to 10 atmospheres, cooled, and filtered to free it from dust, carbon dioxide, and water. Then it is cooled again. Further compression to 200 atmospheres and further cooling liquefies the air. Nitrogen, which is more volatile, is allowed to boil away (at a temperature of -196°C), leaving a liquid containing about 40 per cent oxygen, which boils at -183°C . This is transferred to a further distillation process which produces liquid oxygen that is about 98 per cent pure. The liquid oxygen is drawn off and stored in cylinders or other storage vessels under pressure. Liquid oxygen is pale blue in colour and strongly magnetic. Countries with an abundance of hydro-electric power manufacture oxygen by the electrolysis of a dilute solution of sodium hydroxide (NaOH).

In the laboratory, oxygen can be made by heating a suitable oxide or oxygen-containing salt such as potassium chlorate (KClO_3). The oxygen produced in this *thermal decomposition* is usually collected over water. Oxygen is only slightly soluble in water. But this solubility is of extreme importance. Without it, organisms that live in water would not be able to take in oxygen from their surroundings.

Oxygen is an extremely reactive element; it combines directly with many elements and compounds, particularly when they are heated.



Right: Mining bauxite in the West Indies. Bauxite contains alumina (aluminium oxide), one of the many oxide minerals.



A mixture of oxygen and dinitrogen oxide being administered to a mother in labour to help ease the pain. Pure oxygen and oxygen-rich mixtures have many important medical uses.



These reactions are often highly *exothermic* (giving out heat) and are of great industrial and domestic importance as sources of energy: for example, the burning of fuels such as coal, coke, oil, and gas. Industrially, oxygen is used in oxy-acetylene and oxy-hydrogen welding. Steel plants also consume such enormous amounts of oxygen that they often have their own oxygen production plants. Liquid oxygen is used as a major propellant in rockets and missiles.

Oxygen in the air exists in several forms, or *isotopes*. Isotopes are atoms of an element which differ in mass, while behaving chemically in the same way. The difference in mass is due to the difference in the number of neutrons in the nucleus of the atom. Thus, oxygen has three isotopic forms. Most oxygen atoms are of the oxygen-16 isotope (with eight protons and eight neutrons in the nucleus). About 1.8 per cent is oxygen-17 (nine neutrons) and 0.2 per cent is oxygen-18 (ten neutrons).

Ozone

Oxygen atoms can also combine in threes to give a substance called ozone (O_3). Ozone has different physical properties from oxygen, but gives the same products in chemical reactions. The property of elements existing in more than one chemical form with differing physical characteristics is known as *allotropy*. There is an equilibrium between the two allotropes of oxygen at ground level, the proportion of ozone depending mainly on temperature. At normal temperatures, the amount of ozone is negligible, only rising to about 1 per cent at 3000°C . The proportion

of ozone increases higher up in the atmosphere, due to ultra-violet radiation from the Sun. The ozone layer in the atmosphere protects the Earth from excess radiation which would make life on land impossible.

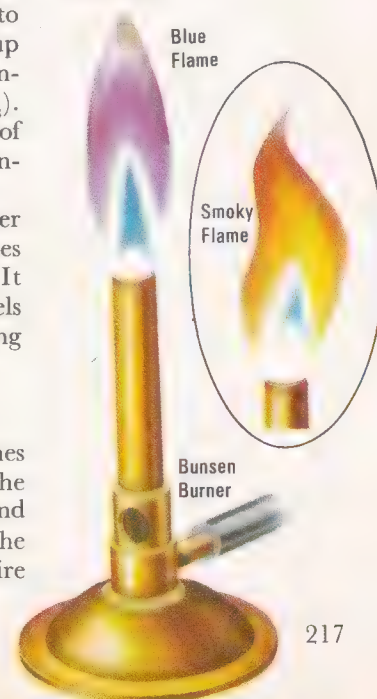
Ozone breaks down quickly into oxygen on heating, a property that presents problems in laboratory preparation. Ozone is usually prepared by passing an electrical discharge across dry oxygen. But the discharge must be 'silent', unlike an ordinary electric spark which creates heat and would therefore decompose any ozone formed. Sparking is prevented by passing the discharge through the walls of the glass tube through which the dry oxygen flows. Oxygen treated in this way contains about 10 per cent of ozone after treatment. The effect of the discharge is to make some of the oxygen molecules break up into atoms, which then associate with undissociated molecules (O_2) to form ozone (O_3). A colourless gas, ozone has a boiling point of -111°C . It is poisonous, though small concentrations are regarded as invigorating.

Ozone is about ten times as soluble in water as oxygen and for this reason is sometimes used in the sterilization of drinking water. It is also used industrially to purify air in tunnels and for bleaching because of its strong oxidizing properties.

Oxidation and Reduction

Under the right conditions, oxygen combines directly with every other element except the rare gases. Because of its reactivity and availability, oxygen figured largely in the experiments of the early chemists. In a desire

Above left: The steel industry has become one of the biggest users of oxygen. The basic-oxygen process has now replaced the open-hearth process as the main method of steelmaking. Above, A crashed aeroplane being sprayed with foam in order to exclude air from potentially flammable materials. Without the oxygen in the air, combustion cannot proceed. Below: The characteristic hot blue flame of a Bunsen burner with the air hole wide open. Inset is the smoky flame with the air hole closed.



to classify the reactions they observed, scientists grouped together all the circumstances where oxygen combined with other substances and called them *oxidation* reactions. In the same way, the term *reduction* was used to describe circumstances where oxygen was removed from a compound. But, in due course, these narrow definitions for oxidation and reduction gave way to more comprehensive ones embodying a much wider range of reactions.

As the scope of chemical knowledge grew, it was realized that many more reactions were fundamentally of the same type as oxidation. Some elements, such as fluorine, chlorine, and sulphur, and other non-metals are *electronegative*. The metallic elements, on the other hand, are *electropositive* (see page 165). An oxidation reaction is said to have occurred when hydrogen or a metal combines with an electronegative element. The term oxidation therefore includes not only reactions involving the addition of oxygen or the removal of hydrogen, but also reactions in which oxygen atoms take no part. For example, the reaction between hydrogen sulphide (H_2S) and bromine (Br_2) to give hydrogen bromide (HBr) and sulphur (S) is an oxidation reaction.

Another important extension to the theory of oxidation was its application to cases where the oxidation number, or valency, of a metal is changed as the result of a reaction. For example, iron(II) chloride (FeCl_2) reacts with chlorine (Cl_2) to form iron(III) chloride (FeCl_3). This is considered to be an oxidation reaction because, in the formation of the iron(III) chloride, the electronegative chlorine atom tends to draw away yet another electron from the iron in the iron(II) chloride molecule. The formula for iron(II) iron is written Fe^{2+} because it has donated two electrons to the two chlorine atoms it is combined with. Iron(III) iron (Fe^{3+}) has donated three electrons. Similarly, changes such as the conversion of copper(I) (Cu^+) to copper(II) (Cu^{2+}) and tin(II) (Sn^{2+}) into tin(IV) (Sn^{4+}) are all regarded as oxidation reactions.

Any process that involves the loss of electrons is thus also regarded as an oxidation. An atom that gives up electrons during a reaction is said to be oxidized, and any substance which habitually increases the valency of a metal by accepting electrons or gives up oxygen is said to be an oxidizing agent. The modern definition of an oxidation is any change in which the proportion of oxygen or any other electronegative element in a substance is increased, or in which there is a loss of electrons.

The process of oxidation is inseparable from reduction, and the definition of the latter has also expanded over the years. It now includes not only the removal of oxygen from a compound, or the addition of hydrogen to it, but also the removal of other electronegative elements, such as sulphur and the halogens. The valency changes in iron and other metals such as iron(III) (Fe^{3+}) to iron(II) (Fe^{2+}) are also regarded as reductions. Substances which usually give up electrons to others or



CARBON OXIDES

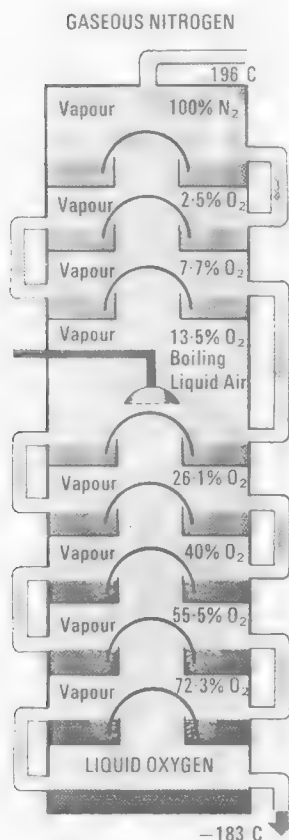
Carbon monoxide (CO) is a colourless, odourless gas which is very poisonous, even in minute concentrations. It is present, for example, in the exhaust fumes from automobile engines, resulting from the incomplete combustion of hydrocarbon fuel. In industry carbon monoxide is an important chemical. It is usually made by passing air or steam through a bed of white-hot coke. When steam is used, hydrogen is also formed. The gas so produced, often called blue gas or water gas, is an important heating gas. Carbon monoxide is also a major ingredient of coal gas. It burns in air with a blue flame, forming carbon dioxide.

Carbon monoxide can be made to combine with hydrogen to form methyl alcohol, or methanol, and this is a very important industrial process. Carbon monoxide is a strong reducing agent. It also combines directly with some metals to form volatile carbonyls. This property is utilized in the Mond process for nickel refining.

Carbon dioxide (CO_2) is present in the air in varying amounts, averaging about 0.03 per cent by volume. It is formed when any carbon-containing material burns completely. It is also produced during fermentation processes, and is given out by animals when they breathe. Plants use carbon dioxide to make food during photosynthesis. Large volumes of carbon dioxide are produced in various industrial processes, including the roasting of limestone to make quicklime (calcium oxide). In the laboratory carbon dioxide can readily be obtained by the action of dilute acids on limestone. Carbon dioxide can easily be liquefied under pressure, and if the pressure is released, a fluffy, snow-like solid forms, called dry ice. It is a convenient portable cooling agent which leaves no mess because it sublimates without melting.

Left: The distillation towers of a liquid-oxygen plant, which can produce up to 3000 tonnes of liquid oxygen a day.

Far right: A fuel technologist conducting research into combustion processes. Temperatures of up to 10,000°C are produced briefly in the tube by means of shock waves travelling at some 11,000 km/h.



A diagram of a fractional distillation tower where the lower-boiling nitrogen is separated from the oxygen in liquid air. Boiling liquid air is introduced into the column half-way up. Vapour travels up through the column and passes through the liquid at each level, which is maintained at a certain temperature. As vapour passes up through the column it becomes richer in nitrogen. As the liquid spills over going down the column, it becomes richer in oxygen.

take up oxygen from them are called reducing agents. A broad definition of reduction is that it is any process which involves the gain of electrons by a substance. Because oxidation and reduction never occur separately, a combination of the two terms—*redox reactions*—is often used to describe them.

All substances which tend to give up electrons are regarded as reducing agents. But the tendency is far greater in some elements than in others. In the same way, oxidizing agents are classified as stronger or weaker by their affinity for electrons. In order that the relative strengths of oxidizing and reducing agents may be predicted, a numerical value is assigned to each element according to its ability to lose electrons. This is called the *standard oxidation potential*. It indicates the general willingness of a substance to lose or gain electrons. The substances at the top of the series, such as the alkali metals and the alkaline-earth metals (for example, lithium and calcium respectively), lose their electrons most readily, and are therefore the strongest reducing agents. The elements at the bottom of the table have the greatest affinity for electrons (for example, oxygen and fluorine), and are the strongest oxidizing agents.

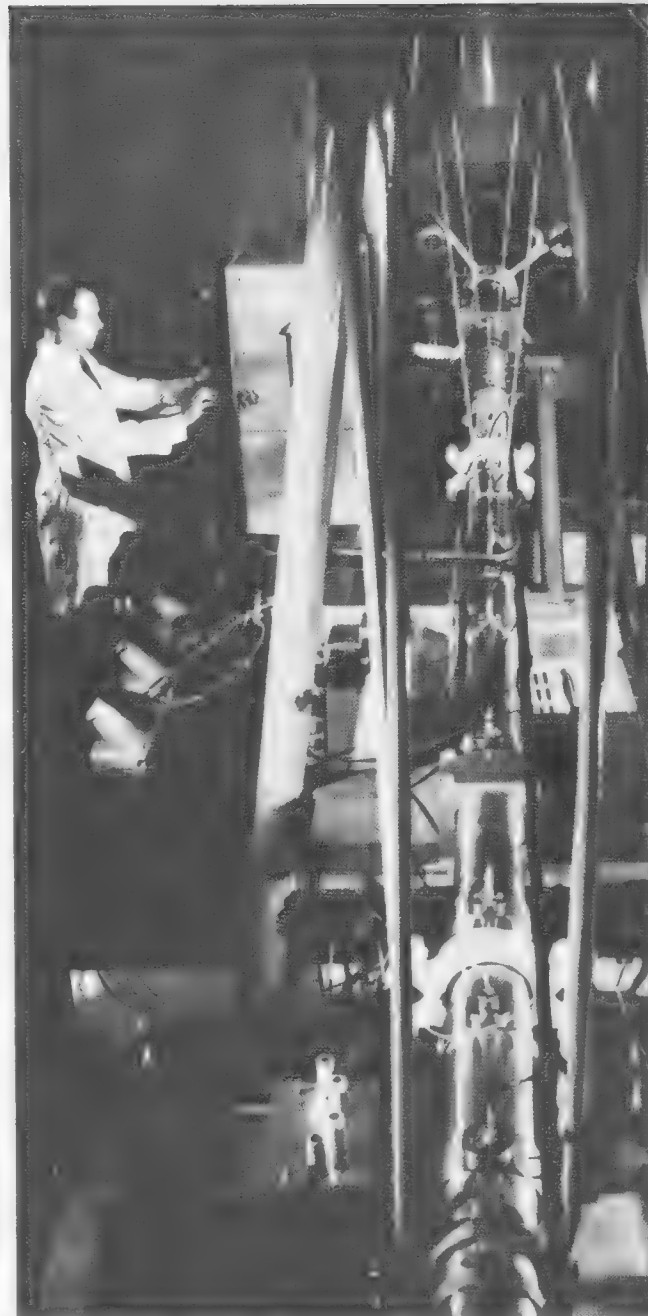
A practical application of this knowledge is shown in methods of protecting metals against corrosion. Iron, which is lower in the table than zinc (Zn) or aluminium (Al), is commonly used in the construction of ships. If exposed to the water, iron will rapidly corrode, due to an oxidation reaction. This corrosion can be slowed by the use of aluminium blocks bolted to the steel of the ship. Aluminium has a greater tendency to lose its electrons and therefore corrodes more quickly than the iron, transferring electrons to it in the process. The aluminium is therefore sacrificed, and this sacrificial protection of the iron tends to prevent its ionization, so that it remains intact.

Combustion

Nearly all oxidations are exothermic, especially those where oxygen combines directly with other elements or compounds. Even rusting, the oxidation of grey coloured iron or steel to the familiar red oxide, gives out some heat, but it is immediately dissipated to the surroundings. More obvious examples of exothermic oxidations are those involved in burning, or combustion.

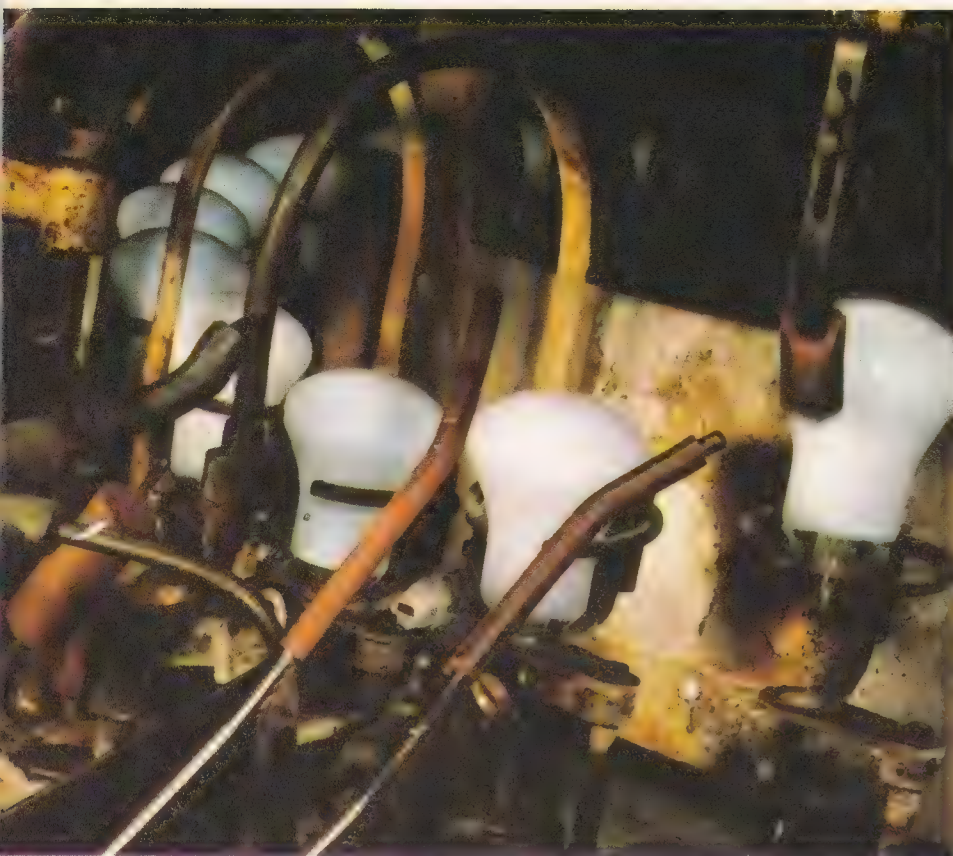
Combustion is defined as a chemical reaction or series of chemical reactions in which a substance combines with oxygen producing heat, light and flame.

The Bunsen burner used in laboratories for heating materials demonstrates how flames differ with the amount of oxygen consumed in the reaction. With the air valve fully closed, the gas burns with a yellow or luminous flame. This is because oxygen can only mix with the gas from the outside of the flame, leaving unburnt particles of carbon glowing in the flame cone. When the air valve is opened,



oxygen mixes thoroughly with the gas and burns it more efficiently. This produces the familiar blue flame.

Combustion is used to drive machines, such as internal combustion engines. The car engine uses a mixture of petrol and air as a fuel. As the piston rises, compressing the mixture, the spark from the plug causes oxygen molecules to dissociate into active oxygen particles. These particles immediately react with the long carbon-chain compounds in the petrol, breaking them down rapidly with the evolution of energy. The energy causes the breakdown of more oxygen molecules, and therefore more fuel, as the flame front spreads across the combustion chamber. The principle is the same as that used in lighting the domestic fire or firing an industrial boiler. The energy supplied in the lighting process breaks oxygen molecules down into the more active oxygen atoms, which then react with the fuel with the evolution of light and heat.



The Rare Gases

As the name implies, the rare gases occur naturally in only very small quantities. The six gases, helium, neon, argon, krypton, xenon and radon are marked by their lack of reactivity. It was this property that led to them being called the 'inert gases' when they were first discovered. In fact, they are not totally inert and in recent years scientists have succeeded in making some compounds.

The reason for the low reactivity of the rare gases lies in the structures of their atoms. The electron shells are all filled. This means that they do not need to combine with other atoms to try to fill the shells. Most gases have two atoms in their molecules, but the rare gases have only one. In other words, they are *monatomic*. The 'fully filled' electronic structure is sometimes known as the noble gas structure, and the rare gases are also known as the *noble gases*.

The rare gases occupy about one per cent by volume of the air, argon being by far the most plentiful. Some natural spring waters contain small amounts of dissolved helium, neon and argon, and natural gas, particularly that found in the United States, may contain up to two per cent of helium. Helium is also produced in small quantities during the radioactive decay of uranium. It can be obtained from minerals containing uranium by

strong heating. Astronomy has revealed the presence of vast amounts of helium in stars, the older stars containing the most. It is thought that the thermonuclear fusion of hydrogen into helium is the principal source of energy in stars.

Preparation and Properties

The main source of helium is natural gas, which consists predominantly of nitrogen and hydrocarbons. The natural gas is liquefied by cooling under pressure and the residual helium, which liquefies at a lower temperature, is drawn off and passed over cooled, activated charcoal, which removes any traces of heavier gases. Helium has several interesting chemical and physical properties. It is very light, being second only to hydrogen, and for this reason can be used for filling balloons and airships. It is also much safer for these purposes than hydrogen because it does not burn. At very low temperatures, helium is very conductive and maintains liquid properties. For this reason, liquid helium is extensively used in low-temperature studies (*cryogenics*).

Helium is used in gas mixtures breathed by deep sea divers, replacing the nitrogen of the air. Helium is less soluble in the blood than nitrogen and diffuses out more quickly. Supplying a mixture of pressurized oxygen and helium to divers thus lessens the danger of the 'bends'. But it has a strange side-effect. Due to the low density of the medium, the diver's voice appears to be very high pitched and squeaky.

Neon, argon, krypton and xenon are obtained industrially from liquid air. The rare gases are distilled off and passed over activated charcoal cooled with liquid air. The rare gases are adsorbed onto the surface of the charcoal.



Far left: Argon is used as an inert gas in electric-light bulbs. In this picture argon is being injected in the fourth bulb from the right. The second bulb from the right is being sealed.

Right: The airship Goodyear over Rome. It is a non-rigid craft, or blimp, filled with helium. Helium is second only to hydrogen in lightness among the gases and it has the advantage over hydrogen in being non-flammable.

Below left: The vivid orange-red glow of neon tubes outline many of the letters in this shop sign. Neon gives out the glow when subjected to a low-pressure electric discharge.

Below: Liquid helium being used in low-temperature, or cryogenic, research. Its boiling point (-268.9°C) is the lowest of any element, and is only 4.2°C above absolute zero.

Bottom: Another use for rare gases is in inert-gas arc welding. The gas is employed to shield the hot metal from oxygen attack.



The degree of adsorption (the process by which substances are concentrated on the surface of another substance) increases with rising atomic weight. Xenon (atomic weight 131) is thus adsorbed before krypton (a.w. 84), argon (a.w. 40), and neon (a.w. 20). This process is carried out at various temperatures to ensure complete separation of the gases. The only known radioactive rare gas, radon, can be prepared by leaving radium, or one of its salts, to stand in a sealed vessel for a period of several weeks.

When neon is subjected to an electrical discharge at low pressure, a characteristic orange-red glow is produced. For this reason it is widely used in advertising signs.

Argon is principally used for filling electric light bulbs, when it is mixed with about seven per cent of nitrogen to prevent arcing. Gas-filled lamps are more efficient than evacuated ones because the inert gas suppresses the evaporation of the delicate filament during use. This enables the filament to reach a higher temperature without affecting the length of its life. Argon is also often used as a carrier gas in gas chromatography analysis because of its inert properties. It carries the substance being analyzed without reacting with it.

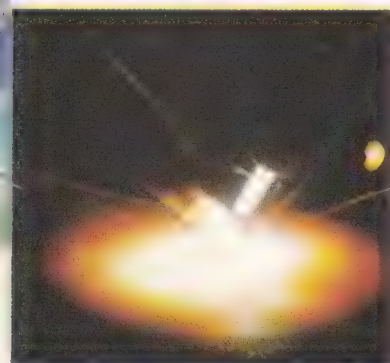
Few uses have yet been found for krypton and xenon. But they are used in some kinds of light bulbs because they conduct heat less readily than argon. This gives the bulbs greater efficiency. Radon is radioactive; one isotope has a half-life of only four days. It is used for treating cancer. A small capsule of radon is buried inside the tumour to irradiate it.

The Stability of the Rare Gases

When the rare gases were discovered, it was realized that they formed a hitherto unsuspected group in the Periodic Table. Although they form no compounds themselves, except under extreme conditions, the structures of the noble gases have provided vital clues to the understanding of chemical combination and bonding. The bonding theory says that, in chemical combination, elements tend to acquire the electron configurations of the rare gases by sharing, donating, or receiving electrons.

Only the rare gases with larger atomic weights have been found to form stable compounds. Xenon, for example, reacts with fluorine when the two gases are heated together under pressure for several hours. The larger atoms react because their outer electrons are held to the atomic nucleus by relatively weak forces. The small atoms of the lighter gases, such as helium, have their outer shells closer to the nucleus. The atomic forces are therefore stronger.

The rare gases can also form other compounds, known as clathrates. These are not formed by means of normal bonding but by the 'imprisonment' of rare gas molecules within the structure of another compound. Quinol ($\text{C}_6\text{H}_4(\text{OH})_2$) is a substance with a very open crystal structure. When it is crystallized from solution in the presence of argon, krypton, or xenon under pressure, the gas molecules are trapped in the spaces in the crystal, forming a clathrate compound. The composition varies according to the number of spaces filled. The enclosed gas is released when the clathrate melts.

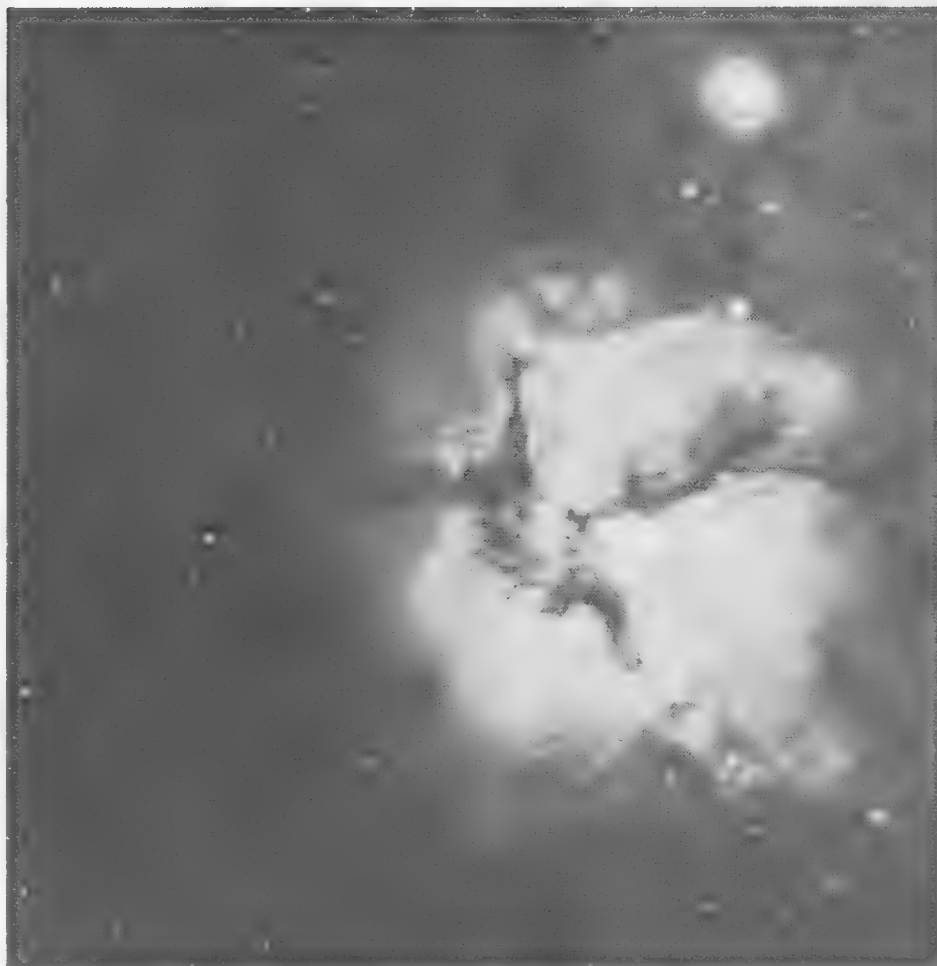


Hydrogen

Hydrogen is the lightest of all the known elements. By itself it forms a colourless, odourless gas. But very little free hydrogen is found on Earth. Small amounts are found in natural gas. The atmosphere contains less than one part per million of free hydrogen, and most of this occurs in the upper atmosphere. Large amounts of hydrogen exist in the sun. There, the nuclear fusion of hydrogen atoms into other elements provides vast quantities of energy.

The discovery of the structure of the hydrogen atom has made a unique contribution to our understanding of the structures of other elements. Normally, the hydrogen atom contains one electron and a nucleus consisting of one proton, but tiny quantities of other isotopes have been found. Hydrogen molecules are *diatomic* (having two atoms), and the element reacts with other substances very easily. Liquid hydrogen boils at -253°C .

Hydrogen occurs naturally combined with oxygen, carbon, and other elements in water, natural gas, and other organic substances. Water is the most important oxide of hydrogen, being essential for all plant and animal life.



But hydrogen can form another oxide called hydrogen peroxide (H_2O_2), which is widely used as a bleaching agent.

The Manufacture of Hydrogen

Large amounts of hydrogen gas are used industrially. In countries with large supplies of natural gas, hydrogen is extracted from methane (CH_4). The methane is mixed with steam and a limited supply of oxygen, and passed over a nickel catalyst at about 900°C . Oxygen is used instead of air at this stage in the process to avoid the formation of nitrogen products. The reaction produces a mixture of carbon monoxide (CO) and hydrogen (H_2), which is then mixed with more steam and passed over an iron catalyst at 450°C to make more hydrogen. Carbon dioxide (CO_2), which is also formed at this stage is removed by washing with water under pressure. Another common method of manufacturing hydrogen is by the *Bosch Process*. The raw material for this process is steam, which is passed over white-hot coke. This breaks down the steam and coke to a mixture of carbon monoxide and hydrogen called water gas. The water gas is mixed with more steam and passed over an iron catalyst to produce more hydrogen and oxidize the carbon monoxide to the dioxide. Hydrogen of high purity can also be made electrolytically. Originally, it was only produced in small quantities during the electrolysis of brine (NaCl) to manufacture sodium hydroxide (NaOH).



Hydrogen has always been seen as a potential fuel, but the high cost of its production has precluded its use. A simple and reactive gas, it is capable of driving internal combustion engines without producing the harmful carbon products associated with petrol. Now that the price of crude oil has risen so much, however, hydrogen is being looked at again. It is possible that, with the increasing amount of relatively cheap electrical power available from nuclear power stations, hydrogen could be produced much more cheaply by electrolysis. It burns cleanly and is easy to store in its liquid form.

Reactions of Hydrogen

Hydrogen always has an oxidation number (valency) of one. With other elements it forms hydrides of two main types. With the alkali- and alkaline-earth metals, such as sodium and calcium, the hydrogen donates its single electron to the metal, forming a solid hydride, which yields hydrogen on treatment with cold water. Hydrogen also combines directly with most non-metallic elements forming volatile, or gaseous, hydrides where the electrons of the two combining atoms are shared. Many of these hydrides are familiar substances. For example, hydrogen combines explosively with fluorine (F_2), even at low temperatures, to form hydrogen fluoride (HF). The reaction of hydrogen with chlorine is explosive in daylight, but proceeds steadily at room temperature in the dark. Hydrogen also reacts explosively with oxygen, if the mixture is ignited. With nitrogen, it hardly reacts at all unless the mixture is heated to a high temperature. Hydrogen is absorbed on heating by certain metals such as platinum and nickel. This phenomenon, known as *occlusion*, is used industrially to purify the gas, since the metal hydrides formed break down on heating to give the pure gas.

In the laboratory, hydrogen is normally generated using a Kipp's Apparatus through the reaction of hydrochloric acid (HCl) on a common metal such as zinc or iron. Hydrogen gas is made up of diatomic molecules, but this is not its most reactive form. Experiments have proved that hydrogen is much more reactive at the moment of generation than when it is collected as a gas. This is probably because, at the moment of generation, the gas is still in its atomic form. At this point it is called *nascent hydrogen*.

Because of its strong affinity for oxygen, hydrogen is a strong reducing agent. When it is heated with iron oxide or copper oxide, the oxide breaks down and iron or copper metal is produced. But it has no effect on the oxides of the alkali- or alkaline-earth metals (sodium, potassium, calcium, and magnesium). This is because of their tendency to donate electrons to the oxygen atoms with which they combine, a phenomenon known as *electropositivity*.

Nascent hydrogen is an even stronger reducing agent than molecular hydrogen and is commonly produced in the laboratory by

mixing dilute hydrochloric acid with zinc. It can also be made from more complex substances such as lithium aluminium hydride ($LiAlH_4$). This type of reducing agent is used in experiments where water must be excluded, making the easier acid/zinc method impossible to use.

Uses of Hydrogen

The reducing properties of hydrogen are widely used industrially. Methyl alcohol (CH_3OH) is manufactured from water gas by passing the mixture of carbon monoxide (CO) and hydrogen (H_2) over a zinc oxide (ZnO) catalyst at $300^\circ C$ and 300 atmospheres of pressure. Hydrochloric acid (HCl) is manufactured by combining hydrogen with chlorine.

Hydrogen can be made to add itself on to the long carbon chains commonly found in organic substances. This is known as *hydrogenation*. An example of its use is in the treatment of plant oils to make margarine. Hydrogenation is also used in the manufacture of synthetic petrol from coal.

Great quantities of hydrogen are used in the Haber process for the manufacture of ammonia, and some, mixed with oxygen, is used in welding. Hydrogen was once used in airships and balloons because it is lighter than air. But after a series of airship disasters caused by the hydrogen catching fire, helium, which is non-flammable, was substituted.

Hydrogen is undoubtedly the most abundant element in the universe, being present in the stars and the gas clouds, or nebulae, between the stars. This picture shows the Trifid nebula in the constellation of Sagittarius. About 12 light-years across, it lies about 3000 light-years away.

Far left: Replacing the fuel elements in a heavy-water reactor. Heavy water is properly named deuterium oxide. Deuterium is the naturally occurring heavy isotope of hydrogen which contains a neutron as well as a proton in its nucleus. In atomic reactors heavy water is used as a moderator to slow down the neutrons produced during fission. This helps to prevent their capture by uranium-238 atoms.

Far right: A battery of reactor vessels used in the hydrogenation of animal and vegetable oils into margarine. Hydrogenation converts the liquid oils into solids.





Water

Water is the most important compound on Earth. It can exist in three states—vapour, liquid and solid (ice). About $2\frac{1}{2}$ per cent of the Earth's water is frozen in glaciers and ice sheets. Most of the rest is liquid. It covers about 70 per cent of the Earth's surface, most of it being water in the oceans. Under the heat of the Sun, water is evaporated from the oceans. When the humidity of the air increases beyond saturation point (the maximum amount of water vapour the air can contain at a particular temperature), droplets of

Zebras drinking at a water-hole in southern Africa. Water is essential to all forms of life — plants and animals alike. As the population increases and industry expands, more and more water is needed.

Below: There is a continual exchange of water between the Earth and the atmosphere, this forming what is called the water cycle. In this cycle water evaporates from the seas, rivers and lakes, and from growing plants. The vapour condenses into clouds in cool air, and returns to the ground as rain, snow or some other form of precipitation.

water form. These mass together as clouds. When the droplets become too large to be held in the air they fall as rain. Most of the rain that falls on land runs into streams, rivers and lakes, and finally back into the sea.

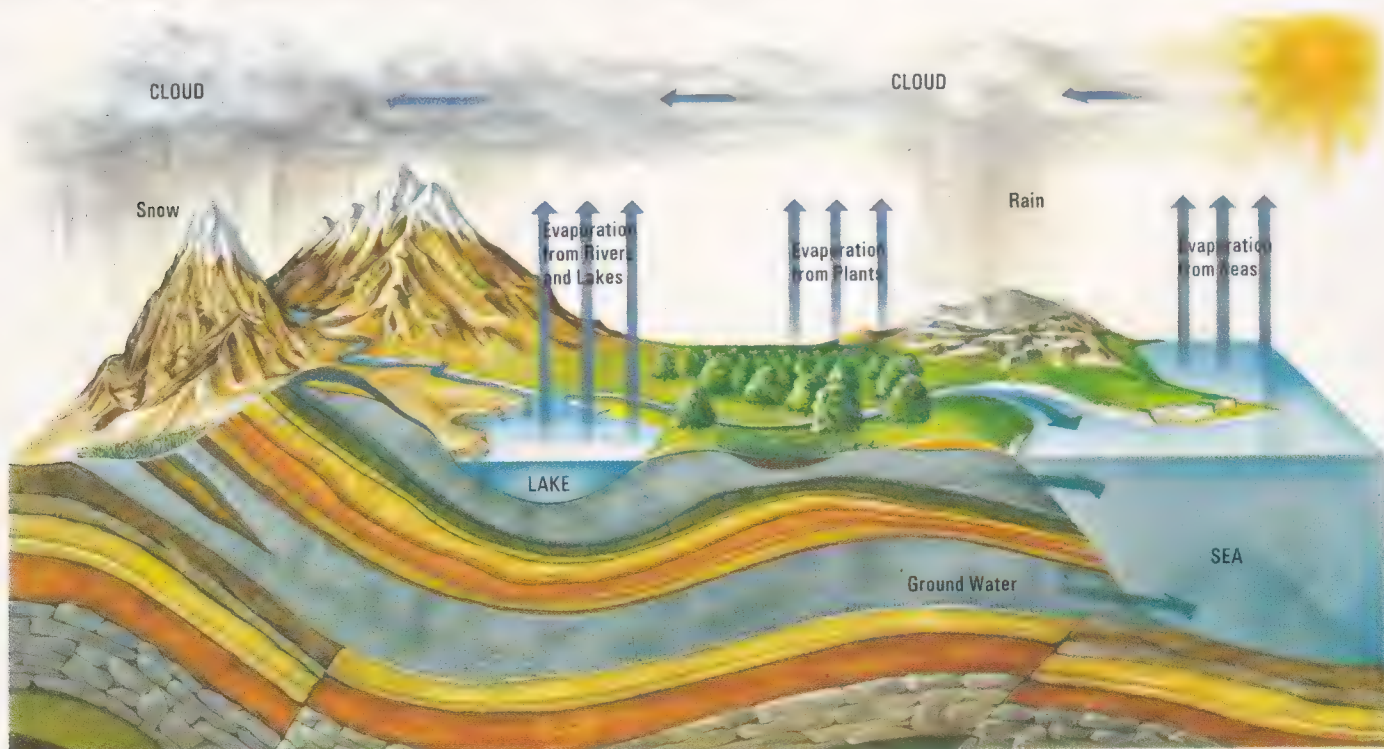
Some water soaks into the soil and becomes *ground water*. Much of this is taken up by plants. Plants, like all other forms of life, depend upon water. It has been estimated that about 450 kilograms of water are needed to produce 500 grams of plant material. Animals also consume large amounts of water. Two-thirds of the human body is water.

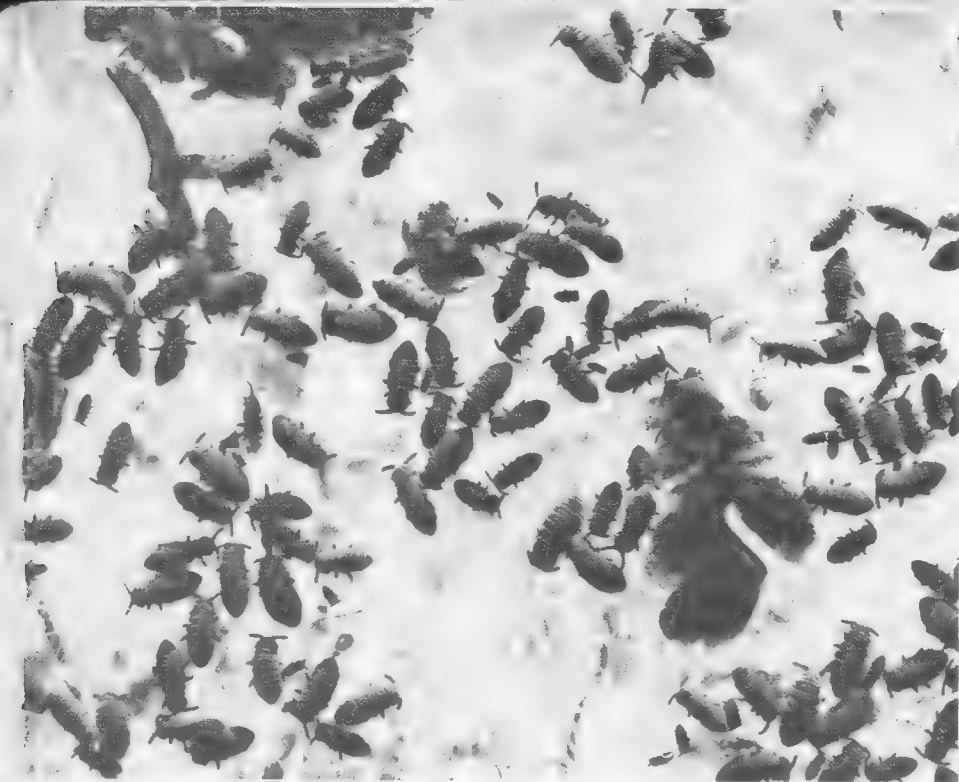
Sea water contains about 3.6 per cent of dissolved salts, the chief of which is sodium chloride, or common salt (about 2.6 per cent). The salts enter the seas from the rivers and ground water that feed them. These waters contain the chlorides, carbonates and sulphates of sodium, calcium, magnesium or iron. Magnesium and calcium carbonates and sulphates cause the water to be *hard*, or resistant to lathering in soap solution. Hardness can be removed by ion-exchange materials, which replace the calcium and magnesium ions with sodium ions, for example.

The Structure of Water

Water is made up of hydrogen and oxygen. Its formula— H_2O —has been established by many experiments. In the laboratory this can be done by the electrolysis of water to which has been added a little sulphuric acid. Pure water does not conduct electricity so the acid is added to complete the electrical circuit. The current breaks up water, giving two volumes of hydrogen for every one of oxygen.

If oxygen is combined with *deuterium* (D_2), an isotope of hydrogen which has an extra neutron in the nucleus, *heavy water* (D_2O) is formed. Heavy water occurs in very small quantities in samples of ordinary water and





is extracted by electrolysis. Normal hydrogen, or *protium*, is discharged preferentially to deuterium, leaving the remaining water richer in heavy water. Heavy water is very important as a moderator in atomic reactors.

The water molecule contains shared, or covalent bonds, but the shared electrons are not symmetrically located. They tend to congregate at the opposite end of the molecule from the hydrogen nuclei. This effectively causes the molecule to have one end with excess negative charge and the other with excess positive charge. In other words the water molecule displays *polarity*. Polarity explains why water is such a good solvent for substances that form electrovalent bonds. The charges on the water molecules tend to pull electrovalently bonded compounds apart. On the other hand water is not a good solvent for covalently bonded substances, such as hydrocarbons.

Because of their polarity, water molecules also tend to cling to ions, forming *hydrates* in aqueous solutions and in crystals. The water that is contained in a crystalline substance is called the *water of crystallization*. For a particular substance this water is always present in the same molecular proportion. For example, the molecules that make up crystals of copper sulphate contain five molecules of water; ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$). Four of these water molecules can be driven off by heating to 100°C , but the remaining molecule requires stronger heating before it can be driven off. This molecule is sometimes called the *water of constitution*.

In water the negative end of one molecule tends to attract the positive hydrogen nucleus of a neighbouring molecule, forming what is called a *hydrogen bond*. Hydrogen bonding explains the frequently anomalous behaviour of water compared with chemically similar compounds, such as hydrogen sulphide, H_2S . Hydrogen bonding causes the water molecules to stick together, giving water relatively high viscosity and high melting and boiling points

The waters of the world teem with life of fascinating variety. The creatures shown above are freshwater springtails, Podura aquatica. They are magnified 15 times.

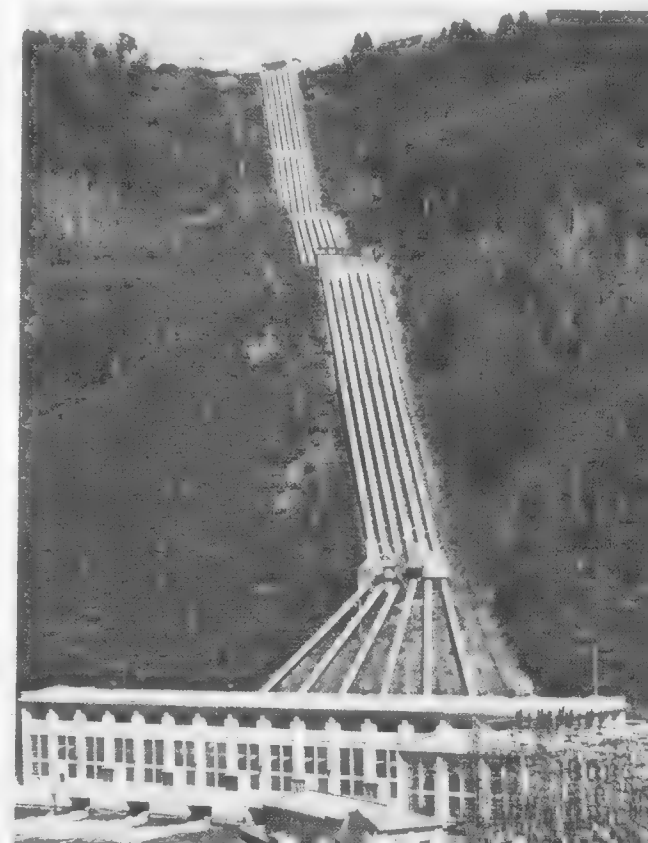
(0°C and 100°C). By rights, compared with similar compounds, water should be a gas at room temperature. In the liquid state molecules of water are packed relatively close together, being at their closest (water being most dense) at about 4°C . In the solid state the asymmetric water molecules organize themselves into an ordered crystal lattice and occupy more space. Solid water (ice) is less dense than liquid water, or to put it another way, water expands on freezing.

Reactions of Water

At temperatures above 2000°C , water breaks up into its elements. It reacts violently with the electropositive alkali metals, such as sodium, at room temperatures, releasing hydrogen. It also reacts with the alkaline-earth metals, such as calcium, on gentle heating. The reaction of water with iron requires a temperature of 700°C and, even then, the reaction is reversible. Carbon reacts with steam to give a mixture of carbon monoxide and hydrogen. The reactions of water with other elements and compounds are so numerous and widespread that they are classed under the general term *hydrolysis*.

Many organic compounds react with water. In some cases, these reactions are so slow that they have to be catalysed by acids or alkalis. But many inorganic compounds react readily with cold water, liberating hydrides. Salts of weak acids and bases undergo hydrolysis in aqueous solution giving acidic and alkaline solutions respectively. Recent experiments have shown that water acts as a catalyst in reactions which are not normally noted for the ease with which they proceed. For example, if dry hydrogen and dry chlorine are mixed together, they react very slowly, but if water vapour is added, the reaction advances quickly to completion.

The power of flowing water has been harnessed by man for centuries. The old waterwheels have now given way to water turbines, which are used to spin electricity generators in vast hydro-electric schemes. The picture shows the penstocks carrying the flowing water down to the turbines in a hydro-electric scheme in Tasmania.



Pollution

Left undisturbed Nature tends to keep itself in balance. Animals take in oxygen when they breathe and give out carbon dioxide. Plants absorb carbon dioxide during photosynthesis and give out oxygen. This interchange keeps the levels of oxygen and carbon dioxide in the atmosphere fairly constant. In a similar way the nitrogen content of the air remains constant. Against this background, numerous species of plants and animals, dependent on each other for their survival, also maintain a balance.

Man, the most intelligent life form this planet has known, has upset the natural balance and threatens himself and indeed all life on Earth with extinction. He is gradually poisoning the land, the sea, and the air. He is also harming the environment in other ways, for example, by making excessive noise and by littering the countryside. Despoilation of the environment, or *pollution*, has become so serious that action must be taken on a global scale. For pollution is not a local problem: when one country detonates a nuclear device in the atmosphere, the resulting cloud of radioactive debris can travel half way round the world before settling as fallout.

The Polluted Air

Large-scale attention was first attracted to pollution problems in the 1950s, when *smogs*—thick, choking, smoky fogs—blanketed many large towns in winter. In London, for example, the 1952 smog resulted in an estimated 4000 bronchial sufferers dying from respiratory complications. The main cause of the smog was fumes from domestic and industrial coal-burning furnaces and grates. Since then various Clean Air Acts, prohibiting the use of non-smokeless fuels have resulted in significantly cleaner air in some regions. London, for example, no longer suffers from smog.

In other regions the situation is not much improved, because of increasing amounts of vehicle exhaust fumes. One of the main causes of atmospheric pollution is the petrol engine. When petrol is burned in the engine cylinders, combustion of the hydrocarbon fuel into water and carbon dioxide is not complete. Some hydrocarbons are not burned, and carbon monoxide is formed. In addition, nitrogen oxides are produced when atmospheric nitrogen is oxidized at the high temperature of combustion. Of these pollutants the most lethal is carbon monoxide. If it is breathed even in amounts as minute as two parts per thousand, it will kill.

Unburned hydrocarbons are not themselves toxic, but they combine in daylight with nitrogen oxides to form a class of secondary pollutants called *photochemical oxidants*. These

EMISSION-CONTROL SYSTEMS

Car manufacturers in many countries are seeking ways to reduce the pollution caused by their engines. Their research concentrates mainly on modifying existing engines to make combustion of the fuel in the cylinder more efficient, and fitting the engines with control devices.

Improvements in combustion efficiency can be brought about in various ways; modifying the carburettor to optimize the air/fuel ratio; reducing the compression ratio; and using electronically metered fuel injection. Controlling ignition more carefully also results in appreciable improvement. One very promising development that lowers exhaust pollution is the *stratified-charge engine*. This is a petrol engine with a modified cylinder head. It has a subsidiary combustion chamber located above each cylinder, in which a rich petrol/air mixture is ignited. This burning mixture then ignites a much less rich mixture in the main cylinder.

One pollution-control measure applied to existing engines is *positive crank-case ventilation*. Despite tight-fitting pistons, some exhaust gases do pass from the cylinder into the crankcase. In the past they were allowed to escape into the air. Now they are channelled back into the engine intake. In another system, excess air is pumped into the hot exhaust stream leaving the engine. This causes much of the unburned hydrocarbons and carbon monoxide in the exhaust to oxidize into harmless water and carbon dioxide. *Manifold reactors*—enlarged exhaust manifolds—have a similar function. Evaporation from the fuel system is a further pollution hazard, but it can be controlled by sealing the system and venting the petrol vapour into the engine intake.

Much controversy centres on a pollution-control device, called the *catalytic converter*. This is a device rushed into production by American car manufacturers in an attempt to meet the demands of the Environmental Protection Agency (EPA). By 1976 all American cars must emit about 90% less pollutants than they did in 1970, and General Motors, for example, has spent nearly \$400 million on the device. The catalytic converter is a component fitted into a car exhaust. It works by incorporating a platinum or palladium catalyst to oxidize unburned hydrocarbon and carbon monoxide. Unfortunately, the catalytic action is inhibited by lead, which is present in most petrols. Also the converter produces a fine mist of sulphuric acid, which itself is a pollutant.

pollutants associate with airborne dust particles and liquid droplets to form smog. The Los Angeles basin is one of the most notoriously smog-prone areas in the world. This is due partly to the vast number of vehicles on the roads, and partly to the geographic location, which encourages a phenomenon called *temperature inversion*. Temperature inversion is a condition in which temperature increases with increasing altitude, which is the reverse of what usually occurs. Inversion results in the lower air stagnating, and this happens especially where there is no air movement sideways (as in the Los Angeles basin). Pollutants entering the atmosphere get trapped and severe pollution results.

Lead is another pollutant derived from the internal combustion engine. Petrol is 'leaded' with lead tetraethyl to increase its octane rating, making it burn more readily in the cylinders. During combustion, volatile lead compounds are produced, and these escape into the atmosphere. Lead is especially dangerous because it accumulates in the body. In cities it is possible that some people are already suffering from a certain degree of lead poisoning. The same goes for people living near lead-smelting plants, which emit a certain amount of volatile lead.

Severe measures are already being taken to curb exhaust emissions from petrol engines, especially in California (because of Los Angeles smog) and in the United States in general. Various emission-control systems are available that can be fitted to existing engines. These appreciably reduce pollution, but may increase petrol consumption by up to 30 per cent. At a time when petrol is becoming less

Below: Part of Canterbury Cathedral, showing the ravages of atmospheric pollution and the way the stonework has been renovated.





Above: Pollution has 'killed' this river by removing the oxygen from it. So here oxygen is being pumped into the water to enable the river to 'live' again.

freely available, this is obviously a drawback. The answer must eventually lie in the development of an alternative for the petrol engine—for example, a steam or vapour engine, a Stirling hot-gas engine, or an electric motor. These alternative sources of power create little or no pollution; but they are not as yet sufficiently well developed for widespread use.

One major pollutant in industrial areas is sulphur dioxide, which comes from burning fuels (practically all fuels contain a certain amount of sulphur). It is an acidic gas with a pungent, suffocating smell. In appreciable quantities, it can impair breathing and damage lung tissue. It forms sulphurous or sulphuric acids with moisture in the atmosphere. Rain-fall in industrial areas is therefore acidic, souring the soil, blackening buildings, and accelerating metal corrosion.

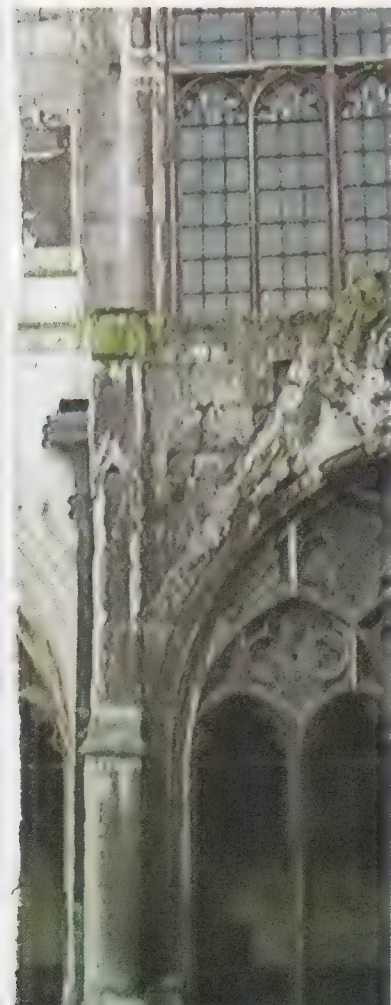
Recently, another potential hazard has been discovered in the shape of aerosol sprays. The propellant gas in these sprays is a compound, such as Freon—dichlorodifluoromethane—or another chloro-fluorocarbon. The danger associated with these compounds is that they interact with the ozone in the atmosphere, converting it into ordinary oxygen. And if the ozone layer were to be significantly weakened, it would no longer be an effective filter for the scorching ultra-violet rays in sunlight. This could lead to increased skin cancer in humans and in the disruption of global weather patterns. Some scientists even think that it could bring about the virtual extinction of life. The prospect of regular flights by high-flying supersonic airliners also poses a threat to the ozone layer. Their engines emit large amounts of nitrogen

oxides, which also tend to decompose ozone into ordinary oxygen.

Another pollution problem that is causing anxiety in some quarters is the increase in the carbon dioxide content of the air. Every time we burn anything carbon dioxide is produced. A significant increase in the carbon dioxide content of the atmosphere could cause its temperature to rise, and this is bound to affect the climate, which again is in a state of fine balance. Any significant increase in temperature could possibly cause the polar ice caps to melt, with disastrous consequences for the great many inhabited regions not far above sea level.

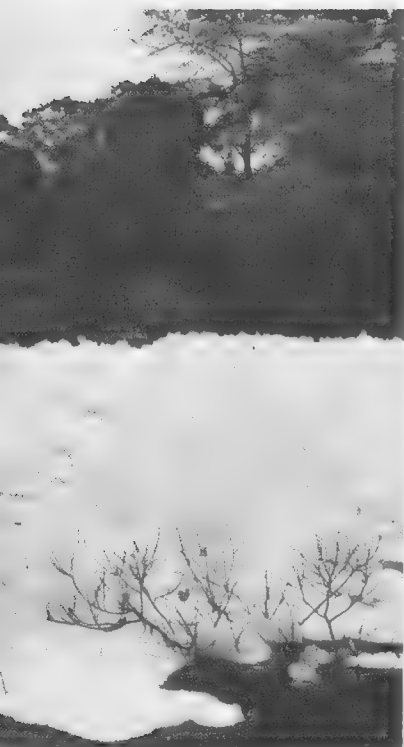
Pollution on Land and Sea

One major cause of pollution in some countries is raw sewage. When properly treated, sewage can be broken down into harmless products and clean water, which can be channelled into the rivers. The rivers are also able to cope with a small amount of raw sewage; aerobic bacteria cause it to break down. But too much sewage will overload this biological self-purification process, and the river becomes devoid of oxygen. Everything living in it dies, and it becomes foul-smelling and a potential health hazard. It has been estimated that it would require the raw sewage from only 100,000 people to deoxygenate the River Thames. Coastal towns are bad offenders in this respect—it is far cheaper to discharge sewage into the sea than to build an expensive sewage-treatment plant. The tendency is to think that the seas have a fathomless capacity for sewage or any other waste material. But this is not the case, as is now being increasingly





Above: The air of our cities is choked with exhaust fumes, smoke and dust, which can cause smogs to form. This view of New York City shows the smoky haze that often gathers around the roof tops of big cities. Left: Not a winter snow drift but a river choked with detergent foam. Such sights are not as common as they once were, thanks to advances in detergent technology and sewage treatment.



MINAMATA DISEASE

In 1950 the Chisso Corporation of Japan opened a petrochemical factory at the fishing port of Minamata, which began discharging effluents into Minamata Bay. The effluents contained a highly toxic methyl mercury compound that eventually became absorbed in the bodies of shellfish and fish, which constitute a major part of the diet of the local people. By 1953 the level of contamination had become so great that it began affecting many of the people.

Within the next decade 106 local people had died a horrible death, howling in pain and racked with convulsions. Many others became blind, deaf, or mentally deranged. In 1963 a body of scientists identified methyl mercury from the Chisso plant as being the cause of the tragedy. Henceforth mercury pollution poisoning has been referred to as Minamata disease. By 1975 Chisso had paid 793 victims more than £30 million in compensation.

realized. The Mediterranean sea is already so badly polluted that bathing is banned in some areas because of the high risk of infection.

Oil is another unpleasant pollutant at sea and will continue to be while crude oil is being carried by tanker and undersea pipeline. Damage to either can result in disastrous spillage, which may give rise to oil slicks several kilometres wide. They contaminate sea birds and foul beaches.

Industrial effluents of many kinds are discharged into the rivers and seas, bringing their toll of dead fish and plants, and stinking, foam-flecked water. Cadmium and mercury compounds are among the most toxic substances discharged. They may become concentrated in the food chain to such an extent that people eating fish taken from polluted waters become ill or even die. Mercury poisoning alone has caused many deaths (see 'Minamata Disease' on this page).

A similar danger is presented by the use of fungicides, pesticides, and herbicides in agriculture. By using these chemicals, farmers are able to increase the yields of their crops, but at the same time they create a potential or actual hazard. In the 1950s and early 1960s indiscriminate use of organochlorine seed-dressings resulted in the deaths of millions of birds that ate the seeds. Another insidious effect of pesticides is that they often become concentrated in the food chain, causing harm not at the source, but later on. DDT, for example, caused birds of prey, at the end of a food chain, to become infertile. DDT also accumulates in body tissues. So does a similar pesticide called dieldrin. Both are present in the body tissues of large sections of the human population. It is not yet known at what level they will begin to affect a person's health or reproductive ability.

Unrestricted use of fertilizers, especially nitrates, is also causing pollution problems. The trouble begins when the fertilizers are washed into the rivers. There they stimulate plant growth to such an extent that the water becomes deoxygenated, and all aquatic animal life slowly suffocates. Then the plants die and rot, and the water becomes foul-smelling. This process, called *eutrophication*, has caused severe pollution of the Great Lakes in North America, and elsewhere.

Another increasingly worrying pollution problem is the disposal of radioactive wastes. It is estimated that the United States alone has enough radioactive material to wipe out most of the world's population, if it were accidentally released. The problem will become more acute when fast breeder reactors come into operation. These produce plutonium waste that remains deadly for hundreds of thousands of years. At present the waste is stored in cooled containers deep underground, or dumped into the ocean depths. The risk of the containers fracturing and releasing their deadly contents is small, but many people feel that any risk of this occurring is unacceptable.

Phosphorus

Phosphorus does not occur in natural deposits. It is usually found combined with calcium. The two main sources of phosphorus are phosphorite ($\text{Ca}_3(\text{PO}_4)_2$) and apatite ($\text{CaF}_2 \cdot \text{Ca}(\text{PO}_4)_2$). It is an essential constituent of living things. Teeth and bones are largely made up of calcium phosphate.

Phosphorus is extracted from mineral deposits or bone ash by heating with sand and coke in an electric furnace. The silica (silicon dioxide, SiO_2) in the sand displaces the phosphorus in the mineral or ash. The phosphorus is released as phosphorus(V) oxide (P_4O_{10}), and is then reduced by the coke to phosphorus vapour. The vapour is condensed to the solid under water.

Allotropes of Phosphorus

Phosphorus exists in several allotropic forms, of which the best known are red and white phosphorus. White phosphorus is a whitish-yellow, waxy solid that emits a greenish glow called *phosphorescence* in the dark, and quickly catches fire when exposed to air. For this reason, it is always stored under water. The oxide fumes formed when the white allotrope burns in air are extremely poisonous.

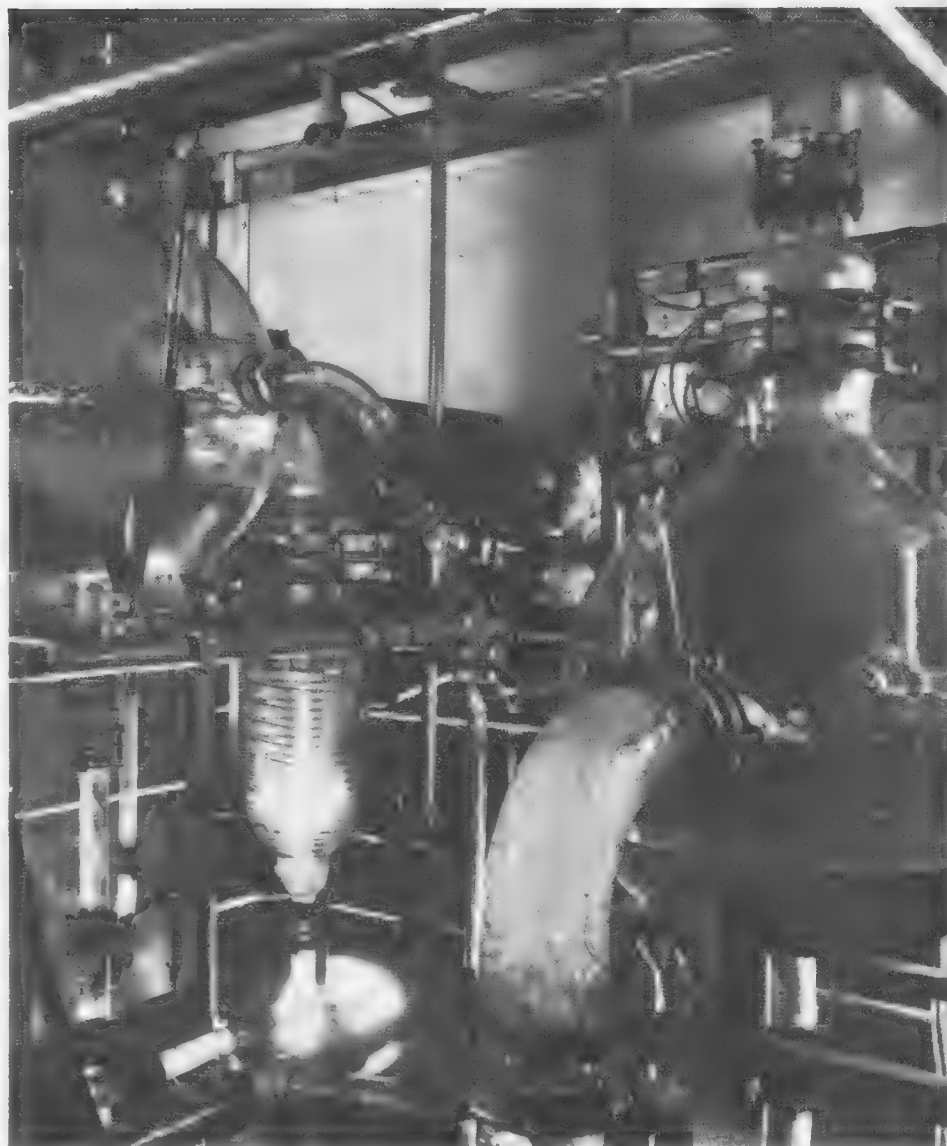
White phosphorus gradually turns into the more stable red phosphorus at room temperature, but this change can be accelerated by heating. Red phosphorus remains stable at all temperatures up to the melting point (600°C under pressure). It is produced industrially from the white form by heating to 260°C in the absence of air.

Violet phosphorus can be made by heating a solution of red phosphorus in molten lead. Black phosphorus can be made by heating the white phosphorus under thousands of atmospheres of pressure. But these two allotropes are of very little practical importance.

Uses of Phosphorus

Phosphorus molecules contain four atoms arranged in a tetrahedron, linked by shared, or covalent bonds, in the vapour state and in solution. Phosphorus reacts vigorously with air. White phosphorus ignites spontaneously, but red phosphorus needs to be ignited. In both cases, however, the oxide produced is phosphorous(V) oxide (P_4O_{10}). This oxide maintains the association of four phosphorus atoms in a similar way to the element, but a molecule of phosphorus(V) chloride (PCl_5) contains only one atom of phosphorus. White phosphorus ignites spontaneously in chlorine and reacts vigorously with bromine (Br_2) and many metals. If red phosphorus is heated with concentrated nitric acid, it is oxidized to orthophosphoric acid (H_3PO_4).

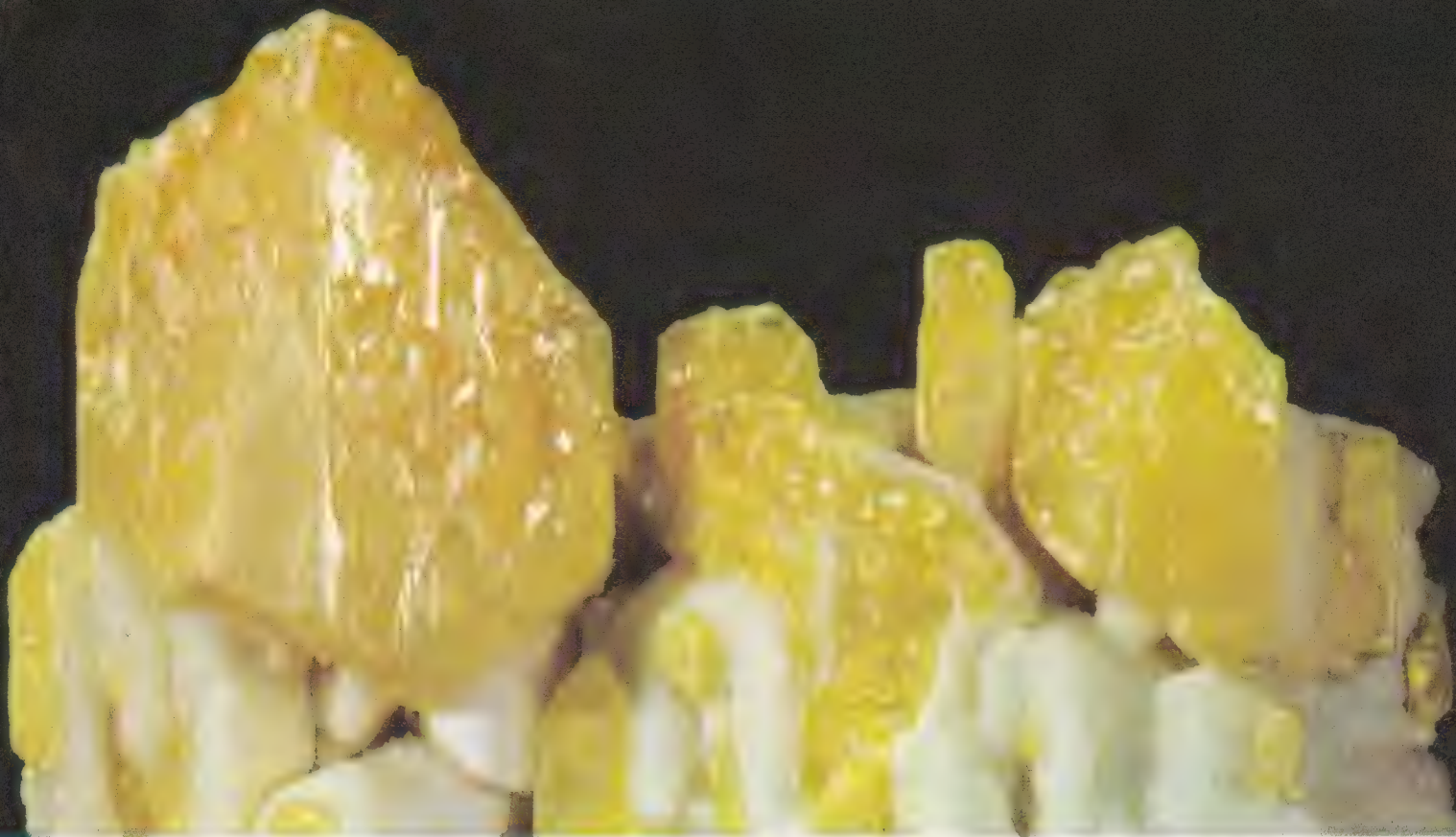
The greatest use of phosphorus is in the manufacture of orthophosphoric acid and its



salts, but smaller amounts are used in producing phosphorus chlorides and phosphor-bronze alloys. These hard, tough and elastic alloys are used for ships' propeller shafts, which have to take great strain. White phosphorus was used in matches until it was discovered to be extremely toxic. Friction matches now contain phosphorus sesquisulphide (P_4S_3) mixed with potassium chlorate (KClO_3), glue, powdered glass, and dyes. Safety matches usually have red phosphorus and antimony sulphide on the box and the oxidizing agent and abrasive in the head.

Another major use of phosphorus is in the manufacture of fertilizers and detergents. The manufacture of superphosphate fertilizers consumes large amounts of both phosphate rock and sulphuric acid. Superphosphate is a mixture of calcium tetrahydrogen di-orthophosphate ($\text{Ca}(\text{H}_2\text{PO}_4)_2$) and calcium sulphate (CaSO_4). It is made by treating phosphate-bearing rock with concentrated sulphuric acid. The diphosphate salt is more easily absorbed by plants than untreated mineral phosphates. Superphosphate is widely used, but an even better product can be obtained by using orthophosphoric acid to treat phosphates, giving triple phosphate.

Part of a plant making phosphoric(V) acid, widely used in the manufacture of the fertilizer triple phosphate. Phosphoric acid also forms the basis of many anti-rust preparations. It attacks rust, forming a layer of iron phosphate, which helps prevent further rusting.



Sulphur

Above: Beautiful crystals of sulphur set in calcite (crystalline calcium carbonate). The crystals are described as orthorhombic. They have a characteristic resinous lustre.

Diagram of the Frasch process for the extraction of sulphur from underground deposits. Hot water and air are piped into the sulphur-bearing rocks, and the sulphur is forced to the surface as a frothy mass.



Sulphur is a yellow, crystalline substance which occurs naturally in large deposits in the United States, Sicily, and Japan. It also occurs as sulphide ores of iron, copper, lead, and zinc and as sulphates of calcium, magnesium, barium, and sodium. Coal, crude oil, and some deposits of natural gas also contain small amounts of sulphur. In the gas it is usually present as foul-smelling hydrogen sulphide, H_2S .

Sulphur is extracted from underground deposits by the *Frasch process*, in which superheated water is pumped down to melt the sulphur and convert it into a low density froth. This thin liquid is pumped to the surface by compressed air, where it is allowed to solidify in large tanks.

Extraction of sulphur from natural gas, by a newly introduced process, now accounts for about 20 per cent of the world's supply.

Sulphur can exist in several forms, or allotropes. The stable allotrope at room temperature is rhombic sulphur, which is made up of yellow octahedral crystals (see above). The crystals are soluble in both carbon disulphide and benzene, but are insoluble in water. Rhombic sulphur conducts heat and electricity poorly. When heated to $115^\circ C$, it melts to a yellow liquid. If this is cooled slowly it solidifies into a mass of yellow needle-shaped or prismatic crystals. This second allotrope is called monoclinic sulphur, which melts at $120^\circ C$. It is only stable above $95.6^\circ C$, and this is known as the transition temperature

between the two allotropes. Monoclinic sulphur reverts to the rhombic form, if left to stand at room temperature. Monoclinic sulphur has a lower density (1.96 gm cm^{-3}), and only dissolves readily in carbon disulphide.

If molten sulphur is heated strongly a series of changes is seen. It darkens in colour with increasing temperature, turning orange, brown, and almost black. At about $200^\circ C$ the liquid becomes so thick that it is possible to turn the vessel upside down without the contents falling out. Above $250^\circ C$, the viscous fluid becomes a dark-coloured mobile liquid, which boils to an orange vapour at about $444^\circ C$. If near-boiling sulphur is poured into cold water, a yellowish-brown, elastic solid forms, called plastic sulphur. Left exposed to air, plastic sulphur gradually loses its elasticity, becoming powdery and brittle.

Sulphur is a reactive element, combining directly with hydrogen, chlorine, carbon, bromine, phosphorous, and nearly all metals on heating. It burns in air to form sulphur dioxide and some sulphur trioxide. Sulphur dioxide (SO_2) is, perhaps, the most important compound. A colourless, pungent, poisonous gas, it is mainly used industrially for the production of sulphuric acid (H_2SO_4), and sulphate products. It is also used as a food preservative.

Large amounts of sulphur are used in the vulcanization of rubber, the manufacture of matches, fireworks, medicinal products, and dyes. Sulphur dust is used as a fungicide in agriculture, particularly for dusting grape vines. Molten sulphur is often run into tubular moulds for sale as roll sulphur, familiar in the laboratory. When sulphur is distilled and condensed to a solid, the product is known as flowers of sulphur, which is partially soluble only in carbon disulphide.

The Halogens

Right: A zinc bromide window to a radiography room in a hospital. Such windows are used to protect viewers from the radiation being used in the treatment.

Below: Fluorite, calcium fluoride, has the fascinating property that it will emit this beautiful violet glow when it is irradiated with ultra-violet rays. The glow is caused by the presence of minute traces of rare-earth minerals.



Far right: Painting a cut finger with iodine — or rather tincture of iodine, a solution of iodine in potassium iodide, alcohol and water.

Below: Iodine crystals under a microscope.



The halogens make up the last family of elements in the Periodic Table. The members of the group, fluorine, chlorine, bromine, iodine, and astatine, display remarkably similar properties, the most reactive element being fluorine. All the halogens have seven electrons in their outer shells and they have a tendency to take up another electron to fill the shell and achieve a fully-filled outer electron shell.

The tendency to take up electrons is known as *electronegativity*, and fluorine is the most electronegative element known. It reacts with hydrogen explosively, even at room temperatures in diffuse light. The reactions of the other halogens with hydrogen demonstrate the decreasing reactivity down the group. Chlorine reacts explosively with hydrogen at room temperature in ultra-violet light, but the reaction proceeds smoothly in diffuse light. Bromine will not react with hydrogen at room temperature unless a platinum catalyst is present, and the reaction with iodine, even when catalysed and heated, is slow, reversible, and incomplete.

Fluorine

Fluorine is far too reactive to occur as a free element. It is extracted from minerals, such as fluor spar (CaF_2) or cryolite (Na_3AlF_6), by electrolysis. Traces of fluoride compounds are found in teeth and bones. The addition of fluorides to drinking water is widely practised as a means of slowing tooth decay. Fluorine combines readily at room temperature with silicon, phosphorus, and sulphur, as well as carbon. The alkali- and alkaline-earth metals burn in fluorine at room temperature and most other metals react with it when heated. Some metals, such as copper and nickel, react only slightly, but this is probably due to the formation of a surface layer of the fluoride, which prevents further reaction taking place.

Fluorine is used in the nuclear fuel industry for making uranium hexafluoride (UF_6) from uranium-bearing ores. The hexafluoride is the only volatile compound of uranium and its manufacture is the beginning of the separation process of the isotopes of uranium used in concentrated nuclear fuels. Fluorine compounds with carbon and chlorine are increasingly used as refrigerants because of their inertness, stability, non-toxicity, and thermodynamic efficiency. These compounds are also used as propellants in aerosols. Other fluorides are used in the brewing, timber, and plastics industries. Hydrofluoric acid (HF) reacts with glass and is used for etching glassware. It must, therefore, be stored in plastic or lead containers.



Chlorine

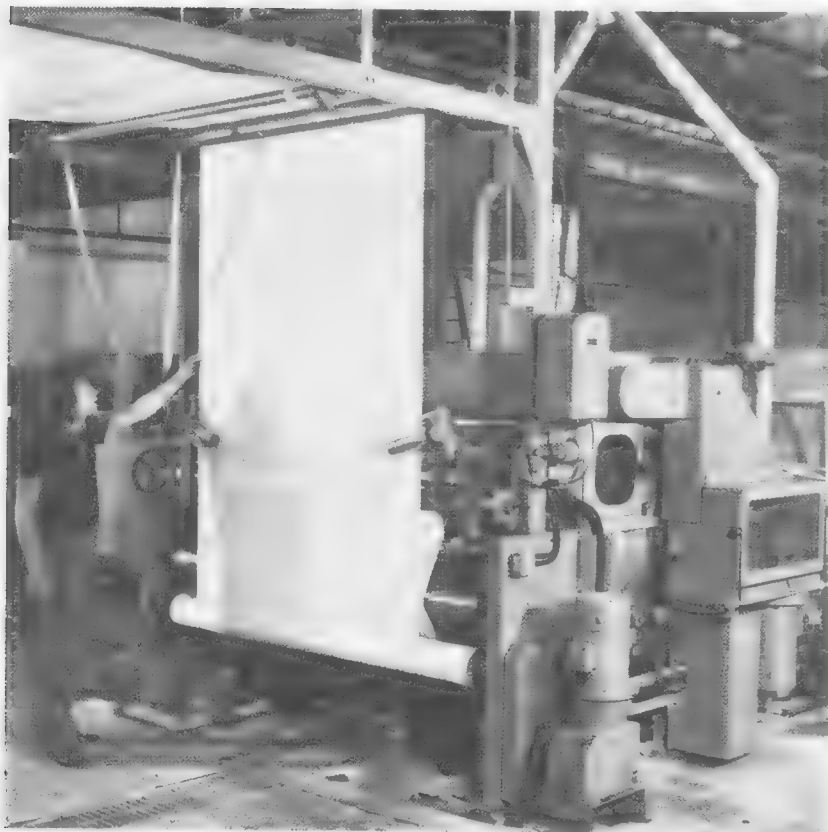
Chlorine, the next member of the family, is also too reactive to be found as a free element. It is usually found combined with metals such as sodium and magnesium. Sodium chloride, or common salt (NaCl), is found in the oceans. It is also found in large quantities in inland seas, such as the Dead Sea, where the water has evaporated and the salt has become concentrated by the sun. Chlorine gas is chiefly obtained by the electrolysis of brine in the Kellner-Solvay cell. It is easily stored and transported as a liquid under pressure.

In the laboratory, chlorine is prepared by heating a mixture of sodium chloride, manganese(IV) oxide, and concentrated sulphuric acid. A greenish-yellow, diatomic gas, chlorine is extremely pungent and poisonous; it was used as a weapon during World War I. Chlorine is fairly soluble in water, and is



highly reactive, though less so than fluorine. It reacts directly with all the elements except carbon, oxygen, nitrogen, and the rare gases but the reactions are often slow unless heat is applied.

More than half the output of chlorine is consumed by the organic chemical industry for the manufacture of dry-cleaning agents,



Chlorine is a powerful bleaching agent, and one of its major uses is in the manufacture of household and industrial bleaches. The textile industry is the main industrial user of bleaches, which not only whiten the cloth, but also make it more receptive to dyes. Here cotton sheeting is just entering a bleaching machine.

such as trichlorethylene, and plastics, such as PVC (polyvinylchloride). Other products include solvents, drugs, antiseptics, and anaesthetics. Other important uses of the gas include the manufacture of hydrochloric acid (HCl) and metallic chlorides. Elemental chlorine is used for bleaching, purifying drinking water and sewage, and detinning tin plate to recover the tin as tin(IV) chloride. It is also used to make carbon tetrachloride and sulphur monochloride, which is used in the vulcanization of rubber.

Bromine

In common with the first two members of the halogen family, bromine does not occur as a free element. It is found in sea water as compounds of sodium, magnesium, and potassium, and in inland deposits. Bromine is extracted from sea water by treating it with chlorine, which displaces the less electronegative bromine. In the laboratory, bromine is distilled from a mixture of concentrated sulphuric acid, manganese(IV) oxide, and sodium, or potassium, bromide. The bromine vapour is cooled and condensed in a flask.

Bromine is a dark red liquid which gives off a reddish-brown vapour that irritates the eyes and lungs, and is poisonous. It resembles chlorine in its chemical reactions, but it is

less reactive. It combines directly with most elements, though heat is often necessary to start the reaction.

The main use of bromine is in the manufacture of compounds, such as ethylene dibromide. Ethylene di-bromide, added to petrol with anti-knock agents such as lead tetraethyl, prevents lead being deposited in the combustion chamber. The lead is expelled through the exhaust system as volatile lead tetrabromide. Bromine is also used to make bromides, important in medicine and photography, as well as organic bromine compounds.

Iodine

Iodine, the last of the common halogens, is obtained from sea water, seaweeds and Chile saltpetre. Seaweed ash can contain up to two per cent of iodine as compounds, but the main source is Chile saltpetre which contains about 0.2 per cent sodium iodate (NaIO_3). The iodate is treated with sodium bisulphite which reduces it to the iodide. The adding of more iodate liberates iodine. The iodine is filtered off, washed, dried, and purified by sublimation. To extract the element from seaweed ash, the latter is mixed with hot water and the filtered solution is evaporated to remove the more soluble compounds, such as chlorides and sulphates. The iodides remaining in the liquid are then heated in iron pots with concentrated sulphuric acid and manganese(IV) oxide. The iodine is distilled and purified by sublimation.

Pure iodine is a lustrous black solid which vaporizes slightly, even at room temperatures. The element melts at 114°C and boils at 184°C . When heated up to about 700°C , it gives off a violet vapour which contains diatomic molecules. The vapour is both irritating and poisonous. Iodine is only slightly soluble in water, but dissolves readily in many organic solvents. It gives a violet solution in solvents that do not contain oxygen, such as carbon tetrachloride (CCl_4), chloroform (CHCl_3), and carbon disulphide (CS_2), and a brown solution in solvents, such as ethyl alcohol ($\text{C}_2\text{H}_5\text{OH}$), that do contain oxygen.

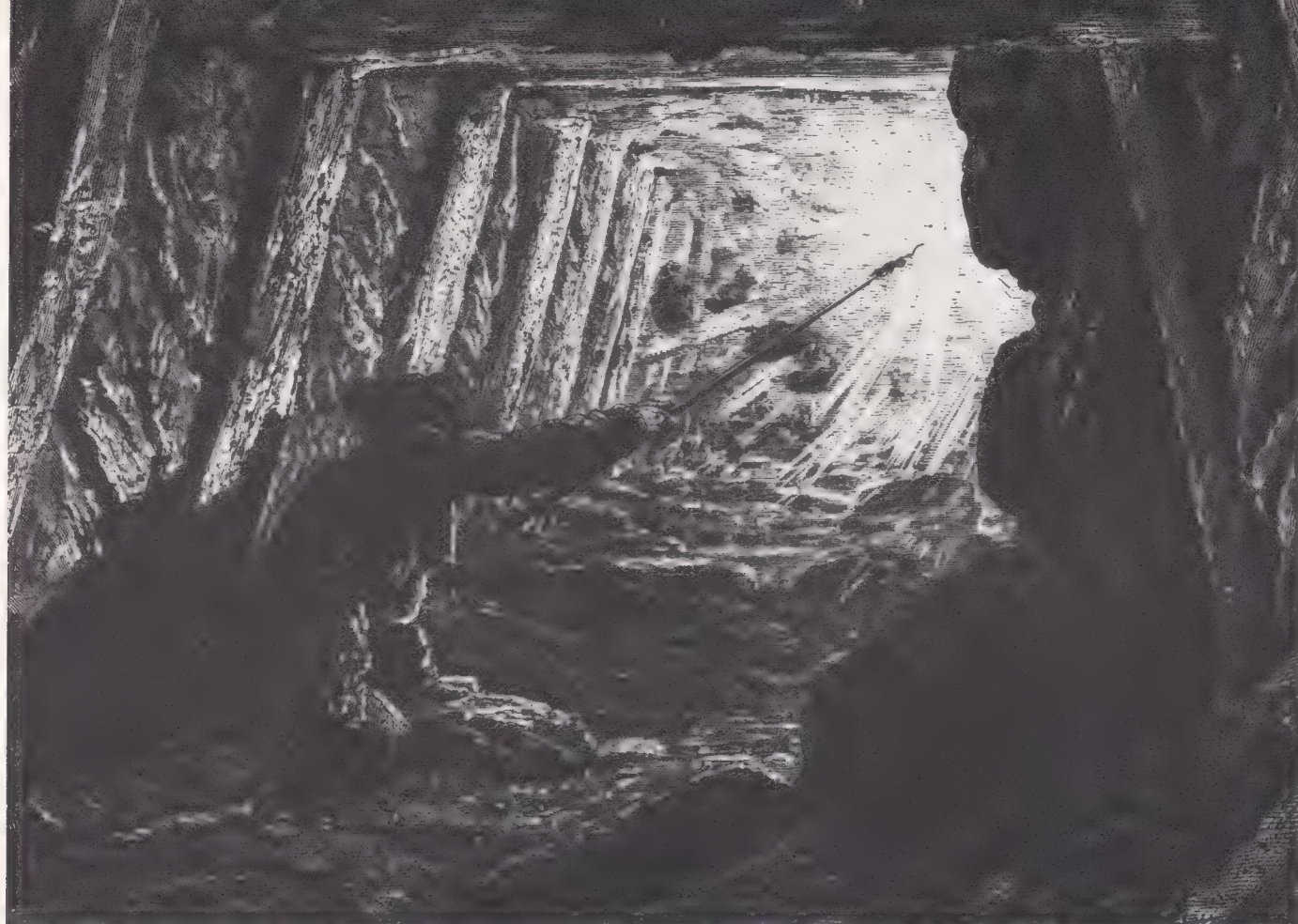
Overall, iodine is not as reactive as the other members of the group. It combines directly with many elements, particularly when heated, to form iodides, but even the reaction with hydrogen, to form hydrogen iodide (HI), is slow and reversible even in the presence of a platinum catalyst. Unlike the other halogens, iodine combines fairly readily with other members of its own group. With fluorine it gives iodine pentafluoride (IF_5) and with chlorine it gives the monochloride (ICl) and the trichloride (ICl_3).

Iodine has powerful germicidal properties; a two per cent solution, known as tincture of iodine, is used as a disinfectant and antiseptic. Iodine is also added to table salt to prevent goitre, a condition caused by a deficiency of the element in the diet.

Carbon[~] Chemistry

Carbon compounds are found throughout nature. Living organisms consist mostly of carbon compounds. Oil is a natural fuel that is formed from organisms that died millions of years ago. It is extracted from the ground by drilling, using an enormous drill pipe and head (right). Many organic chemicals are obtained from the crude oil that comes out of the ground.





Chains and Rings

All the possible arrangements of two to five carbon atoms. The last arrangement of four carbon atoms shown here does not in fact occur in practice. The remainder all occur, demonstrating that carbon atoms can join together in both chains and rings.

The Uniqueness of Carbon

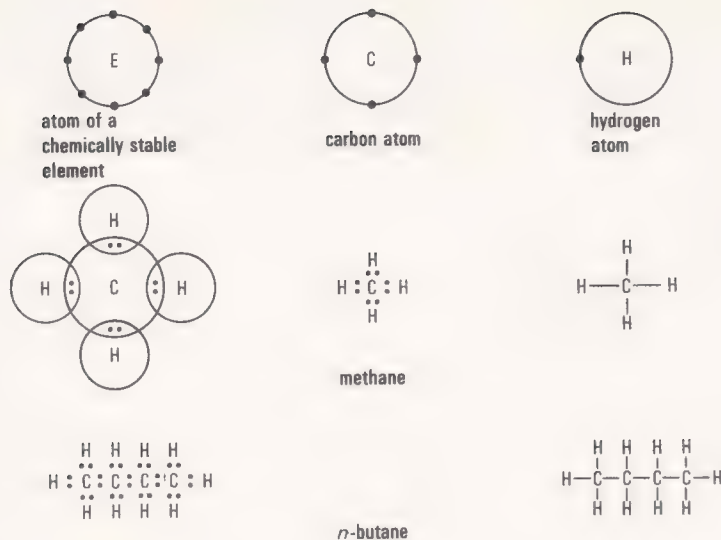
Carbon is a unique element. Its atoms can bond to other carbon atoms almost indefinitely. Many carbon compounds therefore contain chains or rings, or both, of linked carbon atoms. These are the compounds that are studied in organic chemistry; they are also the compounds that make up all organic matter, whether living or dead.

How Carbon Forms Bonds

In organic compounds the most frequent kind of bonding is the type known as *covalency*, in

In early coal mines, one of the major hazards was the highly flammable fire-damp, a gas that is now called methane. Small pockets of the gas would collect near the roof of the mine. It was the job of a miner called the 'penitent', his clothes soaked in water, to crawl in and burn the gas using a torch. With any luck it was not mixed with sufficient air, and therefore did not explode. However, this was extremely dangerous work.

Two carbon atoms				
Three carbon atoms				
Four carbon atoms				
Five carbon atoms				



which pairs of electrons are shared between atoms (see also page 163). An atom is chemically stable if its outer electron shell contains eight electrons. A carbon atom has four electrons in its outer shell. By combining with other atoms in such a way as to gain four electrons—one for each of its own—carbon attains the stable number of eight outer electrons.

Covalent compounds formed in this way abound in organic chemistry. Such compounds contain bonds between carbon atoms, which have 4 available electrons, and many other kinds of atom besides carbon itself. Chief among these other elements are hydrogen (H, 1 electron); nitrogen (N, 3 or 5 electrons); oxygen (O, 2 electrons); sulphur (S, 2, 4 or 6 electrons); and phosphorus (P, 3 or 5 electrons). Living organisms are made up principally from carbon compounds containing these elements (and hence so also is all dead matter).

Carbon's Arrangements

When bonded together in the simplest possible way, a group of three or more carbon atoms

How carbon atoms form bonds. An atom of a chemically stable element has eight electrons in its outer shell. An unstable element, in forming bonds, tries to make up this number. A carbon atom has four electrons in its outer shell, and a hydrogen atom has one electron. Therefore, when carbon and hydrogen combine, to form methane (CH₄), one carbon atom shares pairs of electrons with four hydrogen atoms. One electron of each pair is supplied by the carbon atom, and the other is supplied by the hydrogen atom. The carbon atom thus acquires eight electrons. When two or more carbon atoms combine with hydrogen, shared, or covalent, bonds form in the same way.

can form more than one arrangement in space: the more carbon atoms, the more are the possible arrangements. This is important in organic chemistry because compounds containing different arrangements of the same atoms have different properties. The immense number of carbon compounds made possible by these multiple arrangements accounts for the chemical variety and complexity of organic matter.

The Simplest Carbon Family

Of all carbon compounds, those with hydrogen alone, containing only single bonds, are the simplest. These compounds form a series known as the *paraffin hydrocarbons*, or *alkanes*.

Simplest of the alkanes is methane, a gaseous compound familiar both as natural gas, and in coal mining as firedamp. More complex members include propane and butane, two well-known fuel gases. The higher, or heavier, members of the series are liquids or solids.

Though simple compounds, the alkanes illustrate two very important general properties of organic series. First, since all bonds are 'used up', or *saturated*, in the alkanes, we would not expect them to react easily. They are, indeed, very stable compounds, and, in fact, all saturated organic compounds are unreactive. Secondly, each member of the alkanes series differs from the next higher or lower member by the same chemical group, namely $-\text{CH}_2$. Any such series, where a group can be 'added' successively to make higher members, is known as a *homologous series*, and such series are very common. Each member is known as a *homologue*; thus methane, ethane and nondecane are homologues.

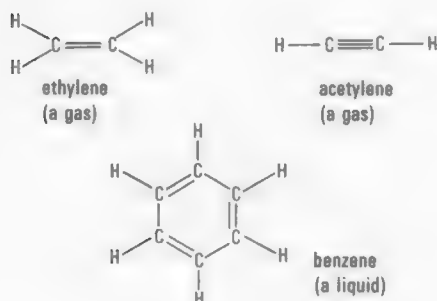
Besides the alkanes, the saturated hydrocarbons include the cycloparaffins, which have a ring structure, and the branched-chain saturated hydrocarbons. 'Carbon skeletons' of both these types are shown on the opposite page.

The simplest family of hydrocarbons are the normal paraffins, or alkanes. They have a general formula $\text{C}_n\text{H}_{2n+2}$.	Structural formula	Empirical or molecular formula	Common name	How derived from previous member	Physical state
		CH ₄	methane		C ₁ to C ₄ are gases
		C ₂ H ₆	ethane	CH ₄ plus CH ₂	
		C ₃ H ₈	propane	C ₂ H ₆ plus CH ₂	
		C ₄ H ₁₀	n-butane	C ₃ H ₈ plus CH ₂	
		C ₅ H ₁₂	n-pentane	C ₄ H ₁₀ plus CH ₂	C ₅ to C ₁₈ are liquids
		C ₁₁ H ₂₄	n-nondecane	C ₁₀ H ₂₂ plus CH ₂	C ₁₉ upwards are solids

Bonds and Energy

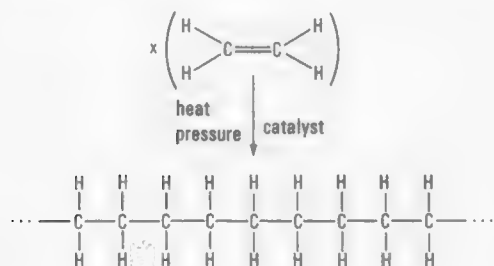
Double and Triple Bonds

The alkanes are unreactive hydrocarbons because they are saturated compounds. That is, the bonding energy of their carbon atoms is largely used up. But other series of hydrocarbons exist in which the bonds are less stable because they contain more energy. These hydrocarbons are more reactive than the alkanes. The high energy bonds are usually referred to as double and triple bonds. Typical examples of hydrocarbons containing such bonds are ethylene, acetylene, and benzene.



Such compounds, like the alkanes, form homologous series in which each member differs from its neighbours by a characteristic chemical group. Examples from these series are shown in the table on the opposite page.

Ethylene and acetylene are unsaturated chain hydrocarbons. Ethylene belongs to the series called *olefins*, or *alkenes*. Acetylene is a member of the *alkynes*, which are also called the *acetylenes*. Their reactivity can be illustrated by the fact that acetylene will explode when compressed and also by the ability of ethylene to react with itself to make a *polymer*. The result of this polymerization reaction is familiar to us as *polyethylene*, or *polythene*. The chemical reaction is as follows:

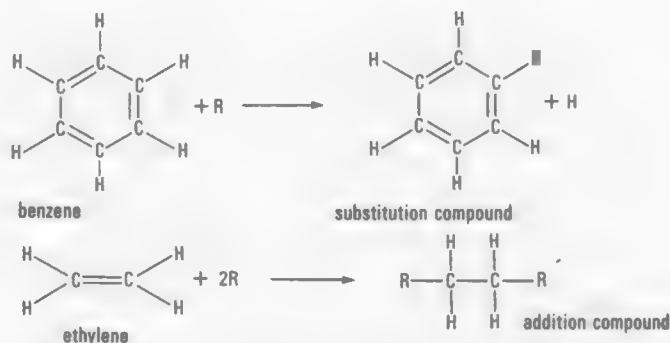


This polymerization reaction gives rise to a saturated (single bonded) long-chain compound, polyethylene, which is more stable and less reactive than ethylene.

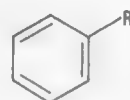
Aromatic Compounds

Benzene is the simplest member of an important class of ring compounds known as *aromatic hydrocarbons*. The word 'aromatic' is used here because these compounds were originally associated with fragrant vegetable materials. Those organic compounds that do not contain a benzene ring are called *aliphatic hydrocarbons*. The formula of benzene can be written as C_6H_6 ; it contains proportionately much less hydrogen even than ethylene, C_2H_4 . But in aromatic hydrocarbons this degree of unsaturation does *not* lead to instability; the benzene ring is, in fact, a stable structure. The reason for this stability is complex but it involves a special kind of bonding which leads to a *resonance structure*. Benzene can be written in a simple form, as shown here. The ring structure and bonds are shown, but not the individual carbon and hydrogen atoms. But the benzene ring can be written in either of the two ways shown here. The double bonds can be drawn in either of the two positions. The actual bonding of the benzene ring is said to *resonate* between the two structures.

The resonance of the benzene ring is associated with its chemical stability. Although benzene is the parent of many compounds, these are formed by *substitution*, and the benzene ring remains intact. Compounds of unsaturated chain hydrocarbons are formed by *addition*, in which double bonds are broken. This situation can be illustrated by two reactions, in both of which R stands for a reacting group.



The substitution compound of benzene can be drawn more simply as shown here. There is only one such compound because the benzene ring is symmetrical and so all positions of R represent the same thing. But if more than one substitution is made in the ring then a number of different compounds is possible. For example, with two substitutions three structures having different symmetries are

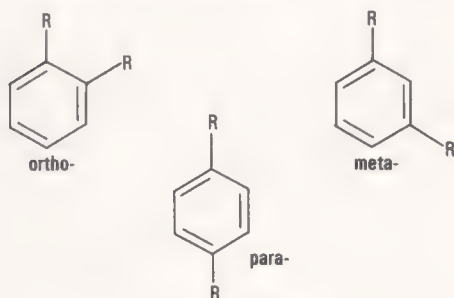


A substitution compound of benzene.

Opposite: Part of a catalytic cracker complex at an oil refinery. Here long chain compounds are heated over a catalyst to break them down into simpler compounds that are more useful as fuels.

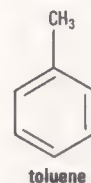
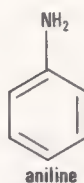
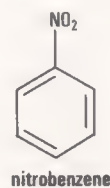
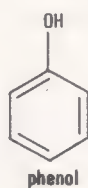


possible and so three different compounds can be formed, designated the ortho-, meta- and par- compounds as shown.



Up to six substitutions can be made in the benzene ring—one for each of the six hydrogen atoms. At the same time any substitution compound of benzene may react with another substance to form yet another compound.

The number of compounds that can be derived from benzene is thus very large and many of them are of great industrial importance. Among the single substitution compounds, phenol, nitrobenzene, aniline and toluene are used widely as chemical intermediates and solvents.



Oil, Energy and Chemicals

All the hydrocarbons mentioned so far, of the straight-chain, branched-chain, cyclic and aromatic kinds, are major constituents of crude petroleum oil and give it many of its properties. Petrol and paraffin are oil products too well-known to need description, but crude oil distillation also gives rise to other fuels such as gas oil and aviation spirit. Lubricating oil and asphalt, used for road surfacing, are other oil constituents.

Of equal importance are the industrial chemicals—petrochemicals—derived from petroleum. Some of these chemicals, such as propylene and butadiene, are in turn starting materials for the manufacture of polymers in the rubber and plastics industries.



Acetylene can be burned with oxygen to produce a very intense, hot flame. Oxyacetylene torches are used for welding and brazing (above).

Examples of unsaturated hydrocarbons. These all contain double or triple bonds.

Chemical Name	Other Names	General Formula	Type of Bond	Members of the Series			
alkenes	olefins	$C_n H_{2n}$	double bond, straight chain	Structural formula			
				Condensed formula	$H_2C=CH_2$	$H_2C=CH.CH_3$	$H_2C=CH.CH_2.CH_3$
				Empirical or molecular formula	C_2H_4	C_3H_6	C_4H_8
				Name of compound	ethylene or ethene	propylene or propene	n-butylene or but-1-ene
alkynes	acetylenes	$C_n H_{2n-2}$	triple bond, straight chain	Structural formula			
				Condensed formula	$HC\equiv CH$	$HC\equiv CCH_3$	$H_3CC\equiv CCH_3$
				Empirical or molecular formula	C_2H_2	C_3H_4	C_4H_6
				Name of compound	acetylene or ethyne	methylacetylene or propyne	dimethylacetylene or but-2-yne
aromatic hydrocarbons	none	$C_{2n-6} H_n$	resonance ring structures	Structural formula			
				Condensed formula			
				Empirical or molecular formula	C_6H_6	$C_{10}H_8$	$C_{14}H_{10}$
				Name of compounds	benzene	naphthalene	anthracene

A Wealth of Compounds

Carbon chemistry, or *organic chemistry*, is treated as a separate study from inorganic chemistry because carbon compounds were originally associated only with living organisms. Modern chemists still use this arbitrary division because of the very large number of compounds that carbon can form. It has already been shown that carbon forms compounds that consist of carbon and hydrogen only. These are known as *hydrocarbons*, and they make up a large proportion of carbon compounds. In addition to these, carbon can form compounds with many other elements. After carbon and hydrogen, the next most common element in carbon compounds is oxygen. Alcohols, aldehydes, ketones, carboxylic acids, acid anhydrides, ethers, esters and sugars are all compounds that consist of carbon, hydrogen and oxygen. Other elements that occur frequently in carbon compounds are nitrogen, sulphur, halogens (e.g. chlorine) and some metals. Nitrogen compounds form a large group, and many of them play important roles in the chemistry of living organisms.



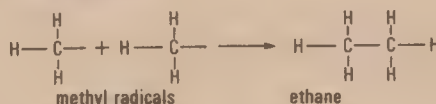
Ethyl alcohol (ethanol) is the product of the fermentation of sugar by yeast. In this distillery the alcohol is distilled and blended to produce whisky.

Radicals

Some chemical groups appear repeatedly in compounds but have only a fleeting life of their own. They react very easily and are known as radicals. An example from previous pages is the $-\text{CH}_2-$ group by which any member of the alkane or alkene series differs from its neighbours. Another widespread group is $-\text{CH}_3-$, the *methyl* radical. Unspecified radicals are generally represented as R (as in the equations on pages 236–7).

In a sense the molecule of any sort of compound can be built up by putting together its component radicals. It is important to note that this combination does not necessarily represent the reactions which actually occur in the laboratory or in industry when the compound is made. For example, the alkane compound ethane, C_2H_6 , can be

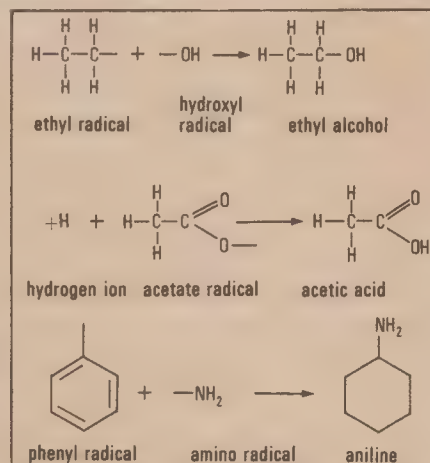
represented as the result of combining two univalent radicals.
















It can also be shown as the combination of a compound and a bivalent radical.



A variety of compounds other than the hydrocarbons can also be built up in this way, demonstrating their component groups. Some of these are shown in the box on the right.



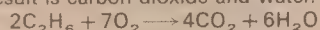
Class of organic compound	Types in class	Structural formula showing characteristic chemical group	Examples		
			chain compounds	cyclic compounds	aromatic compounds
alcohols	primary	$\text{R}-\text{CH}_2-\text{OH}$	CH_3OH methyl alcohol or methanol	 cyclohexanol	 benzyl alcohol
	secondary	$\text{R}'-\text{CH}(\text{R}'')-\text{OH}$	$(\text{CH}_3)_2\text{CHOH}$ propan-2-ol		
	tertiary	$\text{R}'-\text{C}(\text{R}'')_2-\text{OH}$	$(\text{CH}_3)_3\text{COH}$ tert butanol		
aldehydes		$\text{R}-\text{CHO}$	CH_3CHO acetaldehyde or ethanal	 cyclopropanecarboxaldehyde	 benzaldehyde
ketones		$\text{R}'-\text{C}(=\text{O})-\text{R}''$	$(\text{CH}_3)_2\text{CO}$ acetone or dimethyl ketone	 cyclopentanone	 acetophenone or ketone methyl phenyl
acids		$\text{R}-\text{COOH}$	$\text{C}_2\text{H}_5\text{CH}_2\text{COOH}$ acetic acid	 cyclopropanecarboxylic acid	 benzoic acid
anhydrides		$\text{R}'-\text{C}(=\text{O})-\text{O}-\text{C}(=\text{O})-\text{R}''$	$\text{CH}_3\text{COOCOCH}_3$ acetic anhydride		 acetic benzoic anhydride
esters		$\text{R}'-\text{C}(=\text{O})-\text{OR}''$	$\text{CH}_3\text{COOC}_2\text{H}_5$ ethyl acetate	 cyclobutyl acetate	 methyl benzoate
ethers		$\text{R}'-\text{O}-\text{R}''$	$\text{C}_2\text{H}_5\text{OCH}_3$ methyl ethyl ether	 tetrahydropyran	 anisole

Some of the reactants in these equations are ions, such as hydrogen and hydroxyl ions. No clear distinction can be made between ions and radicals. But, in general, organic compounds do not ionize freely, because they are mostly covalently bonded.

There are a number of classes of organic compounds, distinguished from each other by characteristic and specific chemical groups. The first few classes can be grouped together as all those compounds that can be obtained by the oxidation of hydrocarbons under various conditions. Again it is necessary to say that this is merely an arrangement of convenience and the compounds are not necessarily all prepared in this way.

1. Oxidation Products of Hydrocarbons

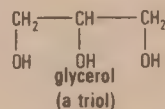
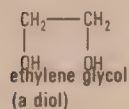
These compounds, by definition, also contain oxygen as well as carbon and hydrogen. If a hydrocarbon compound such as ethane is completely oxidized by burning it in oxygen, the result is carbon dioxide and water.



However, incomplete oxidation of hydrocarbon, using an oxidizing agent with or without a catalyst, gives rise to any of a number of compounds in which carbon is more or less oxidized. Some compounds of this kind, such as ethyl alcohol, acetic acid and acetone, are important chemicals and solvents.

Alcohols are among the least fully oxidized of these compounds. They all contain a hydroxyl group, $-\text{OH}$, attached to a saturated carbon atom, and their names end in *-ol*. The saturated carbon atom distinguishes them from the phenols, aromatic compounds also containing the $-\text{OH}$ group but which have different chemical properties.

Different kinds of alcohols exist according to the degree of substitution in the carbon atom to which the $-\text{OH}$ group is attached. Increasing degrees of substitution give rise to the primary, secondary and tertiary alcohols. Other kinds of alcohols exist which contain more than one $-\text{OH}$ group. These are collectively known as *polyols* and include *diols* and *triols*.



Aldehydes and ketones both contain a carbonyl group, $\text{C}=\text{O}$, and for this reason show resemblances in their chemical behaviour. But they are prepared differently.

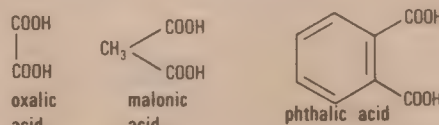
Aldehydes have the general formula $\text{R}-\text{CHO}$ and their names end in *-al*. Thus, they are more oxidized than primary alcohols ($\text{R}-\text{CH}_2\text{OH}$); also they are less so than acids ($\text{R}-\text{COOH}$). It is not surprising, then, that aldehydes can be prepared by oxidizing alcohols or by reducing acids.



Acetaldehyde and benzaldehyde are chemicals of industrial importance.

Ketones can be prepared by oxidizing secondary alcohols. Unlike aldehydes they cannot be easily oxidized because their terminal carbonyl group, $\text{C}=\text{O}$, is already fairly well oxidized. The names of ketones end in *-one*. Acetone and acetophenone are among important ketones.

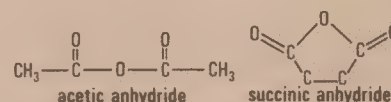
Acids containing the carboxyl group $\text{O}=\text{C}-\text{OH}$ form several homologous series deriving from those of the chain hydrocarbons. The most well-known series is that derived from the alkanes and alkenes, known as the *fatty acid* series because many of its longer-chain members were first obtained from fats. This series has as its three simplest members formic acid, HCOOH ; acetic acid, CH_3COOH ; and propionic acid, $\text{C}_2\text{H}_5\text{COOH}$. These acids can be made by oxidizing the corresponding aldehydes. The table shows examples of cyclic and aromatic acids containing a single carboxyl group. Among the simplest acids containing two carboxyl groups are oxalic acid, malonic acid, and phthalic acid.



Generally, carboxylic acids are fairly strong acids because the carboxyl group undergoes considerable ionization in solution.

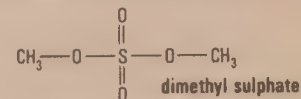


Acid anhydrides, as their name suggests, are compounds that react with water (*hydrolyze*) to produce acids. A few anhydrides, including acetic anhydride and succinic anhydride are important in organic synthesis.



Ethers, which have the general formula $\text{R}'-\text{O}-\text{R}''$, are rather unreactive compounds (as also are most inorganic oxides). The volatile solvent and anaesthetic best known by the name 'ether' is diethyl ether, $\text{C}_2\text{H}_5\text{OC}_2\text{H}_5$. It was prepared traditionally by the action of sulphuric acid on alcohol.

Esters correspond to inorganic salts. Those shown in the table on page 238 are derivatives of organic acids, a representative example being ethyl acetate, $\text{C}_2\text{H}_5\text{OOCH}_3$. Such compounds can properly be considered as oxidation products of hydrocarbons. But another type of ester derives from inorganic acids, for example, dimethyl sulphate.



Many fragrant vegetable oils contain esters. For example, ethyl acetate has the odour of apples.






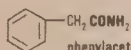
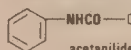

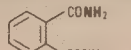
2. Simple Nitrogen Compounds

Next, we can consider the simpler kinds of organic compounds that contain nitrogen: complex nitrogenous compounds of the types occurring in living organisms will be discussed later.

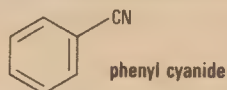
Amines and amides are nitrogenous compounds that are more or less basic in chemical behaviour. The degree of this basicity—the capacity to react with acids—varies. Many amides, particularly aromatic and some aliphatic amides, are very weak bases indeed. Among the strongest bases are the aliphatic amines. The table below lists examples of these and other compounds together with the chemical groups which typify them.

Opposite: Examples of oxidation products of hydrocarbons, showing the chemical groups that define each class of compound.

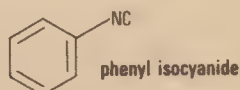
Right: Examples of organic bases that contain nitrogen, showing the chemical groups that define each class of compound.

Class of organic compound	Types in class	Structural formula showing characteristic chemical group	Examples			
					Ring compounds	
amines	primary	$\text{R}-\text{N}-\text{H}$	CH_3NH_2 methylamine	a diamine $(\text{CH}_2)_2(\text{NH}_2)_2$ ethylenediamine	 aniline	 cyclopropylamine
	secondary	$\text{R}-\text{N}-\text{H}$	$(\text{CH}_3)_2\text{NH}$ dimethylamine		 n-methylcyclohexylamine	
	tertiary	$\text{R}-\text{N}$	$(\text{CH}_3)_3\text{N}$ trimethylamine		 n-dimethylcyclohexyl-methylamine	 pyridine
quaternary ammonium compounds		$\text{R}-\text{N}^+$	$(\text{CH}_3)_4\text{NOH}$ tetramethylammonium hydroxide	$(\text{CH}_3)_2(\text{C}_2\text{H}_5)_2\text{NCl}$ dimethyl diethyl-ammonium chloride		
amides	primary	$\text{R}-\text{C}(=\text{O})-\text{NH}_2$	CH_3CONH_2 acetamide or ethanamide		 phenylacetamide	
	secondary	$\text{R}-\text{C}(=\text{O})-\text{NHR}$	CH_3CONHBr bromoacetamide		 acetanilide	
	tertiary	$\text{R}-\text{C}(=\text{O})-\text{NR}_2$	$\text{HCON}(\text{CH}_3)_2$ dimethylformamide		 n-dimethylcyclohexanecarboxamide	
	diamides	Acid group $\text{N}-\text{H}$	$\text{CO}(\text{NH}_2)_2$ urea or carbamide	$(\text{CO})_2(\text{NH}_2)_2$ oxamide	 phthalimide	

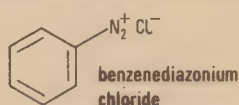
Nitriles, or cyanides, contain the group $C \equiv N$. Examples are acetonitrile or methyl cyanide, CH_3CN , and Benzonitrile or phenyl cyanide.



Isonitriles, or isocyanides, contain the group $N \equiv C$ and are compounds notorious for their intolerable, suffocating odour. An aromatic (only in the sense that it contains a benzene ring!) example is phenyl isocyanide.

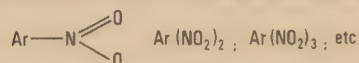


Diazonium compounds contain the group $N \equiv N$ and are very reactive. Diazomethane, $CH_2N \equiv N$, is the simplest example. Aromatic diazonium compounds, $ArN \equiv NX$ (where Ar is an aromatic group and X is any basic group) are much used in organic synthesis, particularly in the manufacture of azo dyes. An example is benzenediazonium chloride.



The plus and minus signs in the formula indicate the compound ionized in solution: diazonium salts are too explosively reactive to handle when dry.

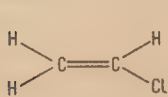
Other very important 'building blocks' in organic chemistry are the *aromatic nitro-compounds*, which have the general formulae:



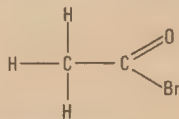
As might be expected, these compounds can be made by the nitration of aromatic hydrocarbons by nitric acid, sulphuric acid also being present to take up water of reaction. Nitroaromatics include important explosives: see page 252.

3. Halogen and Sulphur Compounds

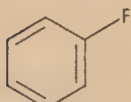
The **halogens** fluorine, chlorine, bromine and iodine form two types of simple organic compounds: *halides*, derived from hydrocarbons, having the general formula $R-Hal$; and *acyl halides*, derived from acids, general formula $R-COHal$. The many uses of these halogen compounds are discussed on page 248; examples of the main types are shown below.



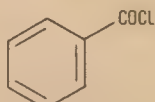
ethylene chloride
(an alkyl halide)



acetyl bromide
(an acyl halide)



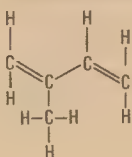
fluorobenzene
(an aryl halide)



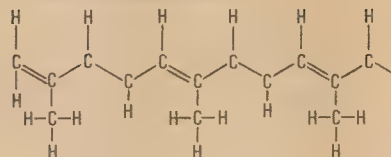
benzoyl chloride
(an acyl halide)

Sulphur is a vital element in the chemistry of life, for example as a constituent of certain amino acids. Other sulphur compounds found in nature tend to have strong and repulsive odours. Butyl and isoamyl sulphides, both secreted by skunks, and *mercaptans*, $R-SH$, secreted by fungi such as the Stinkhorns, have particularly foul odours.

1. isoprene molecule



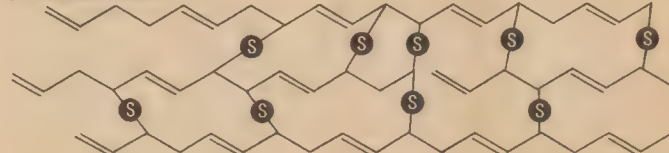
part of a rubber molecule



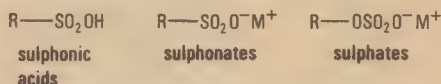
2. unvulcanized rubber



3. vulcanized rubber



Most important commercially of the organic sulphur compounds are those derived from sulphuric acid, the *sulphates*, *sulphonic acids* and *sulphonates*.



In these formulas M is a metal, usually sodium. Sulphonic acids are important in synthesis; sulphates and sulphonates on long-chain carboxylic acids include a number of detergents.

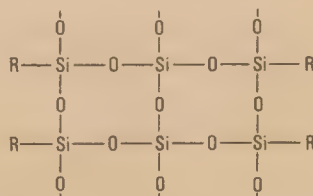
Vulcanization, or the strengthening of rubber by reacting it with sulphur, is another major industrial use of organic sulphur.

4. Silicones and Organometallics

Silicones are quite exceptional organic compounds. They are the only class of chain compounds in which the chain is composed of another element than carbon. A typical silicon has the formula:



and such long-chain molecules can become *cross-linked* to form *silicone resins*.



Applications of straight-chain silicones include lubricating liquids. Cross-linked silicone resins, mixed with fillers, are useful plastics materials. Other cross-linked silicones are rubbers. All silicones are resistant to heat and chemicals and are water-repellent.

Organometallics include the *Grignard Reagents* which have the formula $R-Mg-Hal$, where Mg is magnesium and Hal a halogen. These are among the most important chemical tools of the organic chemist and are employed in the synthesis of compounds ranging from aliphatic alcohols and acids to aromatics such as naphthalenes (see page 249).

1. Isoprene is the monomer of natural rubber. When isoprene polymerizes, many molecules join up to form long chains. Latex that is tapped from rubber trees (below) contains these long chain polymers. 2. In untreated rubber (shown here using 'shorthand versions' of rubber molecules), the long molecules can slide over each other when it is stretched.

3. Vulcanization is a process in which sulphur atoms form cross-links between the polymer molecules, making it heavier and springier than untreated rubber.



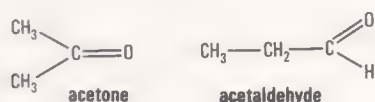
Organometallic catalysts are also often used in organic synthesis. Aluminium forms alkyls, AlR_3 , which are used to catalyze polymerization reactions. Ethylene is polymerized to polyethylene (polythene) using organometallic catalysts containing both aluminium and titanium, for example $TiCl_2 \cdot AlR_3$.

Lithium butyl compounds are useful intermediates somewhat resembling Grignard reagents. Lead tetraethyl, $Pb(C_2H_5)_4$, is the well-known anti-knock compound added to petrol. Zinc diethyl, $Zn(C_2H_5)_2$, was one of the earliest known organometallics: it is a clear liquid that bursts into flame on contact with air.

Isomers



The table on page 234 shows that the same number of carbon atoms can link together in different ways. It follows that a number of different compounds may contain the same numbers and kinds of atoms. For example, acetone (a ketone) and acetaldehyde (an aldehyde) both have the empirical formula $\text{C}_3\text{H}_6\text{O}$ (an empirical formula shows merely the numbers and kinds of atoms present). However, their structures, as well as their chemical properties, are very different.



Compounds having the same empirical formulas but different chemical and physical

properties are known as *isomers*. Isomerism is of great importance in the chemistry of carbon because of the variety and choice of compounds that it makes possible. For example, in the petroleum industry, straight-chain compounds are often converted into more useful branched-chain isomers. A simple case is that of butane, shown above.

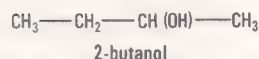
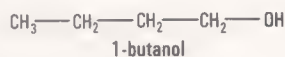
Compounds containing more atoms have more isomers. Pentane (5 carbon atoms) has three isomers; octane (8 carbon atoms) has eighteen isomers; and decane (10 carbon atoms) has no less than seventy-five isomers. Thus, for all the organic compounds that exist, the number of possible isomers is too large to count. But all these isomers fall into only three fundamental classes: structural isomers, geometrical isomers and optical isomers.

Above: Butane has an empirical formula C_4H_{10} . But this compound can exist in two isomeric forms; *n*-butane and isobutane.

Structural Isomers

Two examples of structural isomers are shown above: acetone and acetaldehyde are isomers that differ greatly from each other in chemical properties; *n*-butane and isobutane differ less; both pairs, however, are distinguished as *isomers* merely by the differences in their structural formulas.

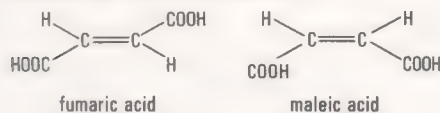
A third example is that of the straight-chain butyl alcohols (butanols).



Here, the structural arrangement differs only in the position of the OH group, indicated in the names by the numbers 1 and 2.

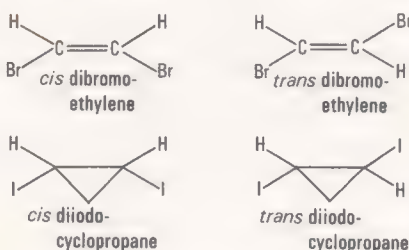
Geometrical Isomers

Geometrical isomers are compounds in which the same chemical groups are arranged differently around a double bond or cyclic ring. A much-quoted example is fumaric acid and its isomer, maleic acid.



This form of isomerism is also known as *cis-trans* isomerism. In this example the *cis*

(same side) isomer is maleic acid, and the *trans* (different sides) isomer is fumaric acid. Other examples are:



Geometrical isomers differ from each other chemically, although not so much as structural isomers of the acetone-propionaldehyde type.

Note that geometrical isomers cannot change one into the other. This is because both double bonds and cyclo rings are high-energy, strained kinds of bonding which do not allow groups to rotate: before this could happen the bonds would break down.

Optical Isomers

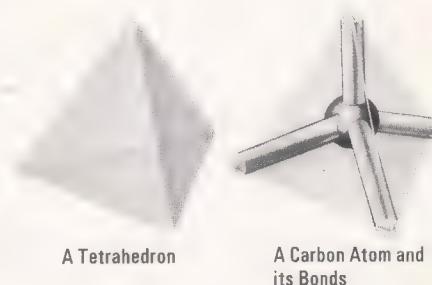
Optical isomers are so named because they rotate the plane of polarized light (light vibrating in only one plane) either to the left, or to the right. Left-rotators are known as *laevo-* or *l*-isomers, and right-rotators are called *dextro-* or *d*-isomers.

To understand what optical isomerism means structurally, we have to look at the

way the bonds of carbon atoms are arranged in space. The diagram below shows how these bonds are directed into space as though towards the corners of a tetrahedron.

In all optical isomers there is at least one carbon atom to which four different chemical groups are attached: the so-called 'asymmetric' carbon atom. Because of the way in which the bonds are directed, asymmetric carbon atoms exist in two forms, which are mirror images of each other. These are the *d* and *l* optical isomers.

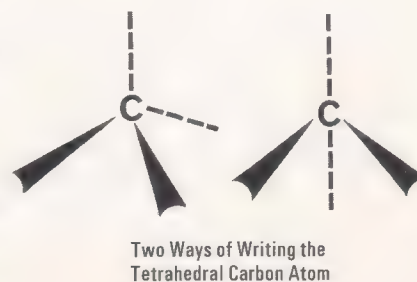
Many such compounds exist in living organisms but, for reasons not completely known, only one of the two possible isomers of any particular type of compound is usually present. For example, among the sugars only the *d* (rotation to the right) isomers are ever found in nature, the most familiar being *d*-glucose. Among the amino acids, on the other hand, only the *l*-forms are found, except in bacteria.



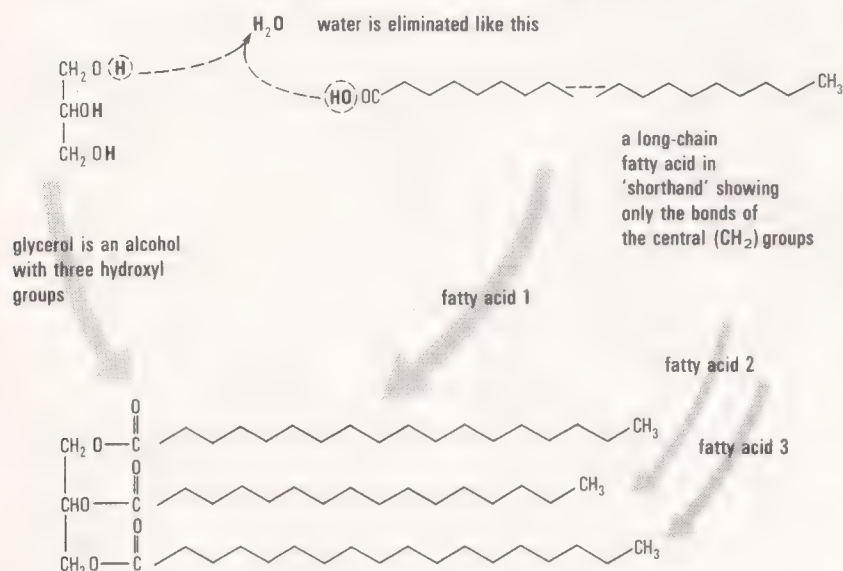
Found in animals and plants	Not found in animals and plants
<p><i>L</i>-alanine</p> $\begin{array}{c} \text{COOH} \\ \\ \text{H}_2\text{N}-\text{C}-\text{H} \\ \\ \text{H}_3\text{C} \end{array}$	<p><i>D</i>-alanine</p> $\begin{array}{c} \text{HOOC} \\ \\ \text{H}-\text{C}-\text{NH}_2 \\ \\ \text{CH}_3 \end{array}$
<p><i>D</i>-glucose</p> $\begin{array}{c} \text{CH}_2\text{OH} \\ \\ \text{H}-\text{C}-\text{O} \\ \quad \diagup \\ \text{H} \quad \text{H} \\ \quad \diagdown \\ \text{OH} \quad \text{H} \\ \quad \diagup \\ \text{H} \quad \text{H} \\ \quad \diagdown \\ \text{OH} \quad \text{H} \\ \quad \diagup \\ \text{H} \quad \text{H} \\ \quad \diagdown \\ \text{OH} \quad \text{H} \end{array}$	<p><i>L</i>-glucose</p> $\begin{array}{c} \text{CH}_2\text{OH} \\ \\ \text{H}-\text{C}-\text{O} \\ \quad \diagup \\ \text{H} \quad \text{H} \\ \quad \diagdown \\ \text{OH} \quad \text{H} \\ \quad \diagup \\ \text{H} \quad \text{H} \\ \quad \diagdown \\ \text{OH} \quad \text{H} \\ \quad \diagup \\ \text{H} \quad \text{H} \\ \quad \diagdown \\ \text{OH} \quad \text{H} \end{array}$

Right: The bonds of a carbon atom are arranged in the form of a tetrahedron. It is sometimes necessary to indicate this when writing formulae. The most usual way of showing the tetrahedral carbon atom is shown in the bottom right diagram.

Left: Examples of compounds that are found in animals and plants, and their optical isomers that are not found in animals and plants.



Longer Chains and Stranger Rings

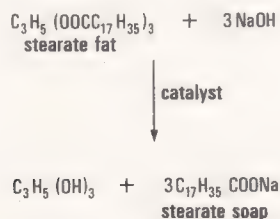


Acids That Make Fats

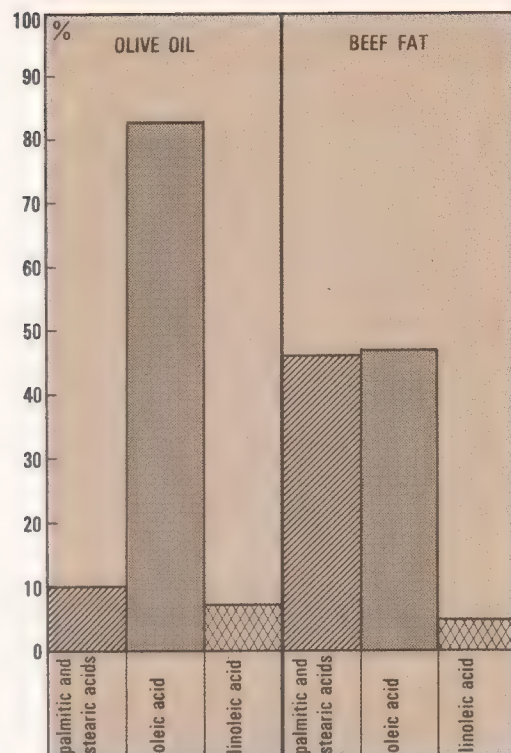
Long-chain carboxylic acids are known as fatty acids. The acids found in animal and vegetable oils and storage fats nearly always have an *even* number of carbon atoms. The four commonest are: palmitic acids, $C_{15}H_{31}COOH$ (16 carbon atoms), and stearic acid, $C_{17}H_{35}COOH$, both of which are saturated acids; oleic acid $C_{17}H_{33}COOH$, which contains one double bond; and linoleic acid, $C_{17}H_{31}COOH$, which contains two double bonds. The diagrams show what part these long-chain acids play in the structure of fats.

Soap, Candles and Margarine

Common soaps are composed mainly of the sodium salts of palmitic and stearic acids. In soap manufacture, fats are first mixed with caustic soda, which provides the sodium, and then steamed. A fat containing only stearate would react to give glycerol and the soap sodium stearate.



Candles are made using *stearin*, a mixture of palmitic and stearic acids. Margarine is made



Above: The proportions of the four most common fatty acids in a vegetable oil and an animal fat.

by churning together any of various mixtures of oils and fats together with 'butterized' milk and emulsifying substances. Vitamins are added for extra food value.

Waxes

Waxes are long-chain compounds, of three distinct kinds. Animal and vegetable waxes are mixtures of esters of long-chain acids and alcohols. Paraffin waxes are simply hydrocarbons of high molecular weight. The diagram below contrasts the structures of these two types of wax.

The third kind, synthetic waxes, are usually polyethers, containing the group $-C-O-C-$ in their polymer chains. These are often used in car polish.

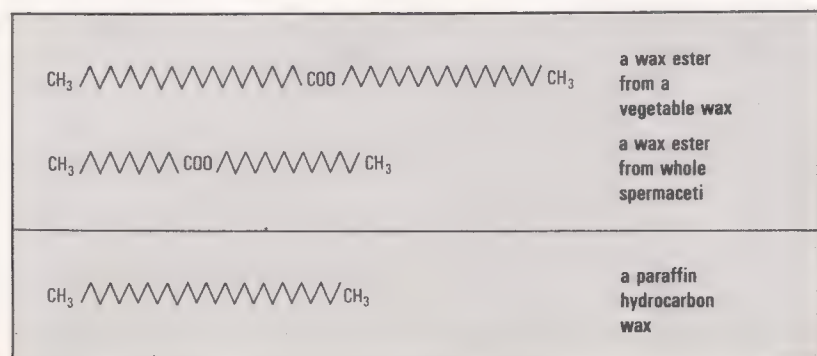
Despite the differences of structure in these three types of compound, they all have similar waxy properties.

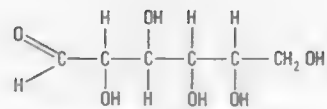
Mixed Rings

So far, the only chemical rings that have been dealt with have been the aromatic and cyclo rings. These all consist of linked carbon atoms.

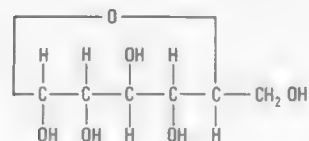
Above: Three fatty acids react with glycerol to form a fat called a triglyceride. This is a typical animal or vegetable fat. It contains oleic acid (fatty acid 1), palmitic acid (fatty acid 2), and stearic acid (fatty acid 3).

Below: The structures of two types of wax. The shorthand formulas drawn here only show the bonds of the CH₂ groups in the long chains.

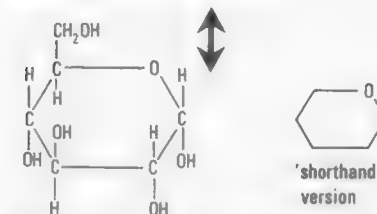




glucose shown as a chain structure



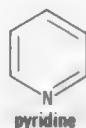
glucose shown as a ring structure



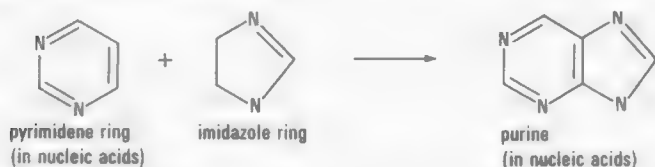
glucose shown as a pyranose (six-sided) ring

Above: Glucose has an empirical formula $\text{C}_6\text{H}_{12}\text{O}_6$. This can be represented as a straight chain, a ring structure or a pyranose (six-sided) ring.

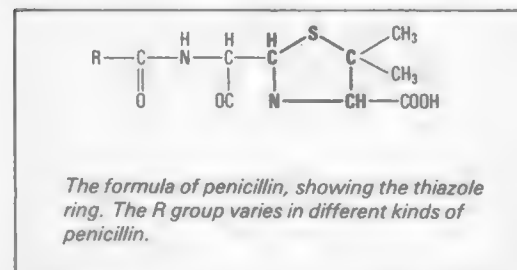
But many carbon compounds contain rings in which other elements as well as carbon appear. An example is pyridine, which is an amine closely related to benzene. Pyridine is an industrial solvent. The pyridine ring appears also in such compounds as Vitamin B₆ and nicotine.



The pyrimidine ring is also six-sided but contains two nitrogen atoms. It appears, together with the imidazole ring, in the nucleic acids: the giant molecules of DNA and RNA (see also page 263).



Rings containing sulphur as well as carbon include thiophene, a minor constituent of coal tar and petroleum. The thiazole ring contains both sulphur and nitrogen and is found in Vitamin B₁ and penicillin.



Rings containing oxygen as well as carbon include those of furan and pyran.

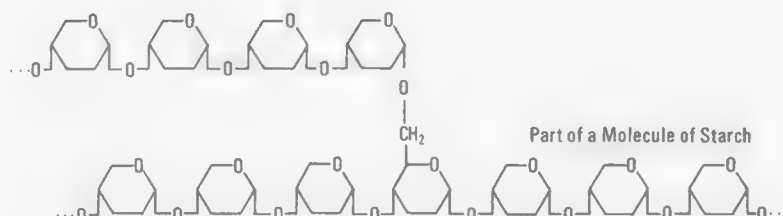
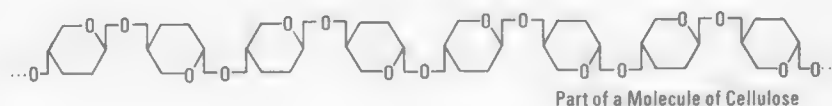


Above left: The hard outer cases of insects, such as this stag beetle, are made up of chitin, a sugar polymer (see page 264). This is covered with a layer of wax, another long-chain carbon compound.

Rings similar to these appear in the five- and six-carbon sugars that are found widely in living organisms. Sugars can be shown either as chains or rings. Glucose, for example, can be shown as a chain structure or as a six-sided pyranose.

Many natural polymers are made up of chains of sugar rings. The two most familiar, starch and cellulose, are both made up of chains of glucose rings. Animal starch, or glycogen, is also made up of glucose units; this compound is stored in the liver until needed for energy.

Below: Starch and cellulose are two natural polymers that have molecules made up of chains of rings. Starch is made up of linked glucose units. Dextrins have the same structure, but are shorter. Cellulose is also made up of glucose units, but these are linked differently, and the chains do not branch.



Chemicals from Fuels

Most of the world's energy supply comes from coal, oil, and natural gas. These fuels are the remains of plants and animals that lived many million years ago. Because of this they are often called 'fossil fuels'.

Coal, oil and natural gas can all be burned to provide heat energy. But, in practice, only coal and natural gas are used directly for this purpose. Oil, also called *petroleum*, is first refined to produce various chemicals, some of which are used as fuels. Coal and natural gas can also be treated to produce chemicals. All three fossil fuels provide chemicals that have many industrial uses, particularly in the plastics and petrochemical industries.

Coal from Ancient Forests

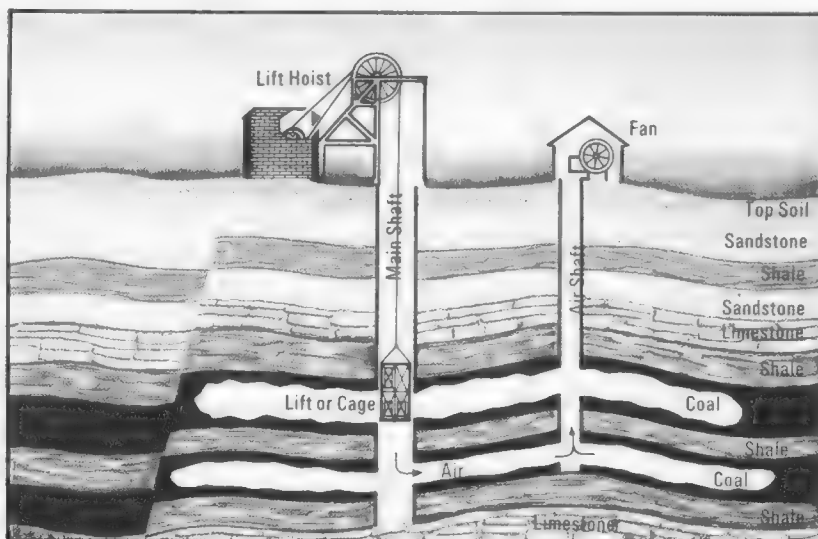
Coal is often described as a mineral, but this description is not accurate. Coal consists of carbon compounds, together with small amounts of sulphur, phosphorus and rock minerals. Coal was originally formed in a similar way to sedimentary rocks. The oldest known coals were laid down during the Silurian Period, some 400 million years ago. But most coals date from the Mississippian and Pennsylvanian Periods (Lower and Upper Carboniferous Periods), 350–300 million years ago.

During these Periods, the climate was warm and damp. Huge tropical seed ferns grew in swampy areas, together with giant non-flowering trees. When these plants died, they fell into the stagnant water where lack of oxygen prevented their complete decay. Instead, a partial decomposition took place through the



Above: Miners drilling a coal face. A pneumatic drill (powered by compressed air) is used, because a drill having an electric motor would produce sparks, and these might cause an explosion. A hydraulic prop, holding up the roof of the tunnel, can be seen on the extreme right of the picture.

Below: A cross-section through an underground coal mine, showing the layers of rock that may occur between coal seams. Men and equipment are moved up and down the main shaft on the lift. Fresh air is drawn through the mine by a pump situated at the top of a separate shaft.



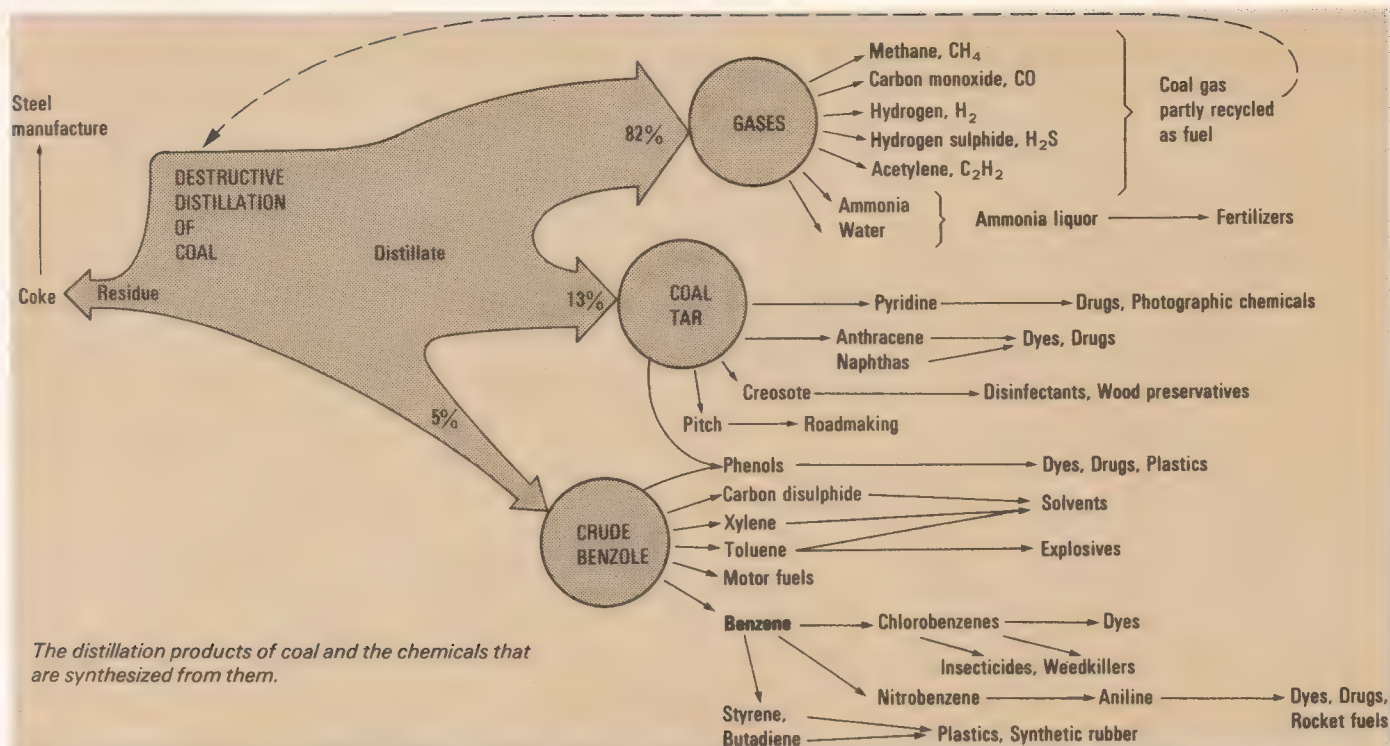
action of certain types of bacteria (anaerobic bacteria) which can survive without free oxygen. The anaerobic bacteria obtained the oxygen they needed from the dead tissues and left behind a slimy material which was gradually compressed into peat.

Over a period of millions of years, the sea covered and uncovered large areas of the land several times. In doing so, it laid down layers of sedimentary rock. Under pressure from the overlying rock the peat dried out and hardened, forming *lignite*, a low grade coal. In areas where the pressure was greater, the peat became compressed to about one-twentieth of its original thickness, and *bituminous coal* was formed. The highest grade coal, *anthracite*, was formed by extreme pressures, caused by buckling and folding of the crustal rocks.

Coal is extracted from the ground by mining. Three methods of mining are used today: *underground or deep mining*; *strip or open cast mining*; and *auger mining*.

Underground mining is used where the coal seams are buried deep in the Earth's crust. The seams may be reached by a vertical shaft, in which case the miners and their equipment have to be lifted up and down the shaft by complex machinery. In slope mines, the seam is reached by a sloping tunnel which makes it easier to transport the coal from the coal face to the surface. Drift mines are those in which the coal face is reached by a horizontal tunnel bored into the side of a hill.

Open-cast mines are used to obtain coal from seams very near the surface. The layers of soil and rock above the coal are removed, and the coal is thus laid bare. In open-cast mines where the overlying rock becomes too thick to remove economically, auger mining is used. Large diameter augers (boring and cutting tools) bore horizontal holes into the coal seams.



A considerable amount of coal is used as an industrial fuel. But it can also be used as a source of chemicals. The *carbonization of coal* is a process in which coal is heated to between 1000 and 1200°C. It then breaks down into four main components: coke, a solid fuel; coal gas; ammonia, containing liquors; and coal tar.

Many important industrial chemicals can be extracted from coal tar. But the demand for coke and coal gas has fallen in recent years, and consequently there is less coal tar available. Coal tar as a source of chemicals is now far less important than oil.

Oil

Crude oil is a mixture of gaseous, liquid and solid hydrocarbons. Scientists believe that oil was formed hundreds of millions of years ago from the remains of tiny marine animals and

Below: Coke, the residue of the destructive distillation of coal, being pushed out of the coke oven.



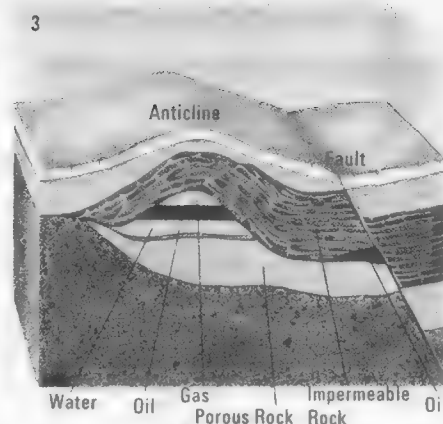
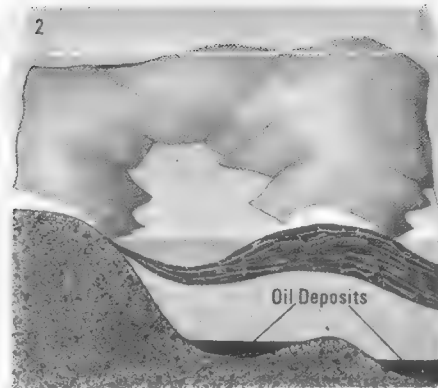
plants by much the same process as that which produced coal from land plants.

The modern oil industry began in 1859, when Edwin Drake undertook the first mechanical drilling for oil. But for the next fifty years production was confined to those places where oil seeping from the ground indicated its presence beneath the surface. By this time the economic value of oil was becoming more apparent. In the rush to find oil, prospectors took to 'wildcat drilling'—a rather speculative process in which the chances of striking oil were one in eight. This continued until the 1950s.

Nowadays there are more sophisticated methods for finding oil. One of the most common techniques is *seismic surveying*. This involves causing small explosions on the surface of the ground. Shock waves from the explosions are reflected and refracted by the underlying rock strata. The nature of the strata can be established from the time taken by the shock waves to travel to recording devices placed around the explosion site. Seismographs are, in effect, maps of rock formation.

Geologists look for certain types of rock formation that are known to be likely oil-bearing structures. The pressure of overlying rocks squeezes the oil droplets through porous rocks towards the surface. An oilfield forms when the oil is prevented from escaping by a layer of impermeable (non-porous) rock. Trapped beneath this 'cap rock' the oil droplets continue to accumulate in the porous 'reservoir' rocks. Water may also be trapped in the same way, in which case the oil, being lighter, floats on top. There may also be a pocket of natural gas above the oil.

The most usual oil-bearing formation is an *anticline*. This is an upfold of rock layers that forms a dome or ridge. If the anticline contains



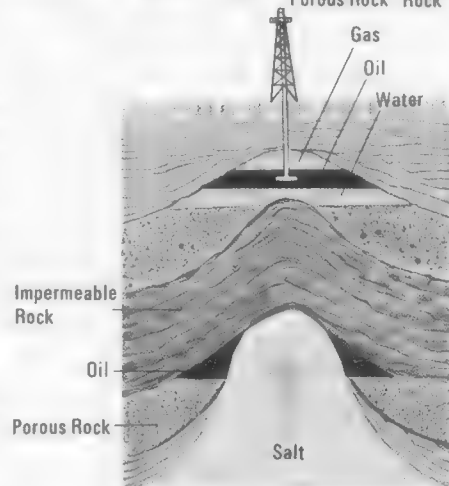
a layer of impermeable rock, oil may be trapped beneath it. *Faulting*, the fracture and movement of rock layers, can also create an oil trap if porous, oil-bearing rocks are moved against impermeable rocks. A *salt dome* is yet another likely place to find oil. This is when a large mass of salt has been forced up from an underground sea that has dried up. The mass of salt forces its way through the rock layers which are tilted and buckled. Oil collects around and above the salt mass which acts as impermeable rock.

Seismic surveys can indicate the presence of likely oil-bearing structures, but the only way to tell for certain whether oil is present in substantial quantities is by drilling. The earliest form of drilling was *percussion drilling*, which broke up the rock by hammering. Nowadays this is only used for very shallow oil deposits, and *rotary drilling* is mostly used. The drilling bit revolves, and is gradually pushed down into the rock. Lengths of drill pipe are periodically added to the other end, on the *drilling platform*. The bit is kept lubricated by a drilling clay (*bentonite*) mixed with water. This is pumped down, and it helps remove the pieces of rock. When oil is reached, the drilled hole, which is lined with a metal casing, is sealed off with cement. A pipeline

Above: 1. The formation of oil began millions of years ago when dead organisms fell to the bottom of the seas. 2. Erosion of the land caused layers of sedimentary rock to be deposited on the partly decomposed remains. Pressure and heat cause the carbon compounds to form the mixture of hydrocarbons that makes up crude oil. 3. The oil seeped up through the porous rocks until it became trapped by impermeable rocks. Geological formations that may contain oil include anticlines and faults.

Right: In a salt dome, a mass of salt from an evaporated sea has been forced up and has sealed the oil-bearing porous rocks.

Below: A drilling rig used to extract oil from under the sea.



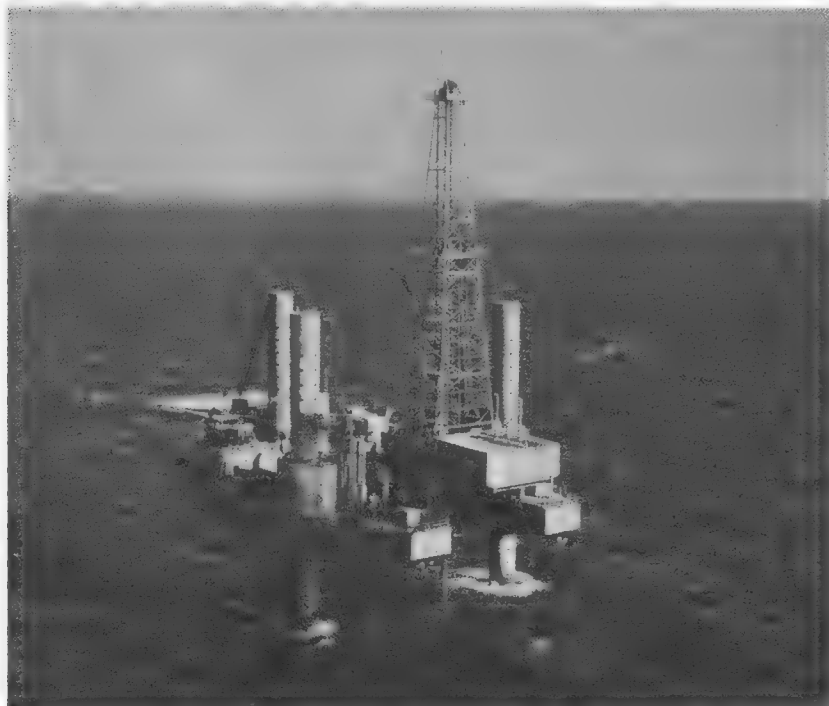
is then connected, the cement seal is pierced, and the oil begins to flow. The oil well is then a *producer*.

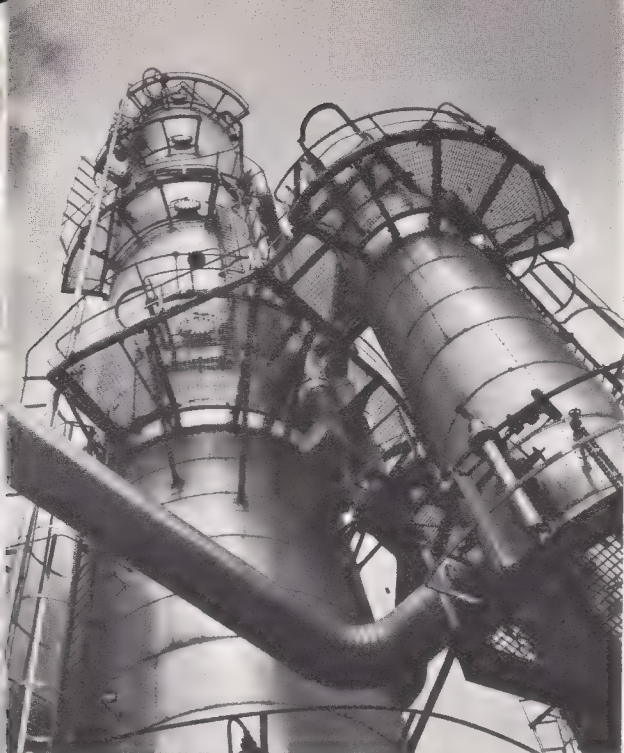
The oil underground is usually under considerable pressure. Initially, therefore, it is forced out. When the pressure drops the oil has to be pumped to the surface. Finally the oil well is flushed out with water. Even so, between 20 per cent and 50 per cent of the oil remains clinging to the rock inside the well.

Refining Crude Oil

The first stage of the refining process is *fractional distillation*. The oil is first heated in a furnace and then passed to a fractionating column. The column is hottest at the bottom and gets cooler towards the top. The chemicals in the crude oil vaporize, and the compounds having the lightest molecules are removed at the top of the column. This *fraction* includes *gasoline*, or *petrol*. In fact the chief use for crude oil is the production of petrol and diesel oil for engines. But fractional distillation does not produce enough of these fractions to meet the demand. The remaining fractions are therefore broken down by *catalytic cracking*. This process breaks down long-chain hydrocarbons into smaller, and therefore more volatile molecules, which can be used in internal combustion engines.

Fractional distillation and cracking also produce compounds that have small straight-chain molecules, such as ethylene, propylene and butylene. Many of these chemicals are used in the plastics and petrochemical in-





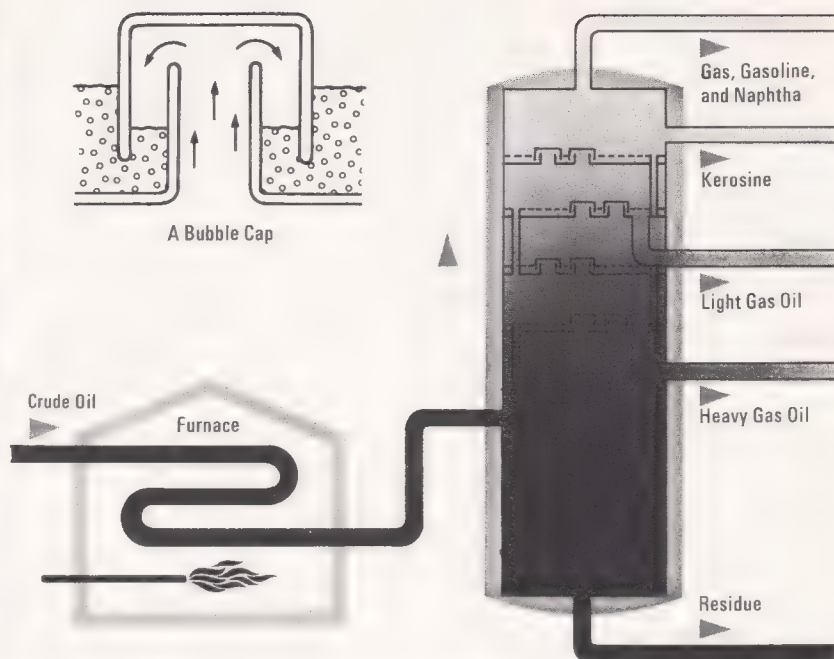
dustries. They can also be converted into branched-chain and aromatic (ring-structured) hydrocarbons by *catalytic re-forming*. The 'reformed' compounds are added to the gasoline fraction to enrich the petrol that is used in cars.

Thus, crude oil contains a wide range of compounds, and many more can be made during the refining processes. From these, many products are made, including plastics, detergents, drugs, fabrics, explosives and dyes.

Natural Gas

When oil deposits were laid down, pockets of natural gas were often formed as well. In some places, the gas is all that is left of the deposit. It is located by the same methods as oil, and, once it has been extracted, it is distributed by pipelines.

A large amount of natural gas is used directly as a fuel. It requires more oxygen than coal gas for combustion, and it has twice the heating value. Unlike coal gas, however, it contains no poisonous compounds (coal gas contains carbon monoxide). Natural gas has no odour, and small amounts of strong-



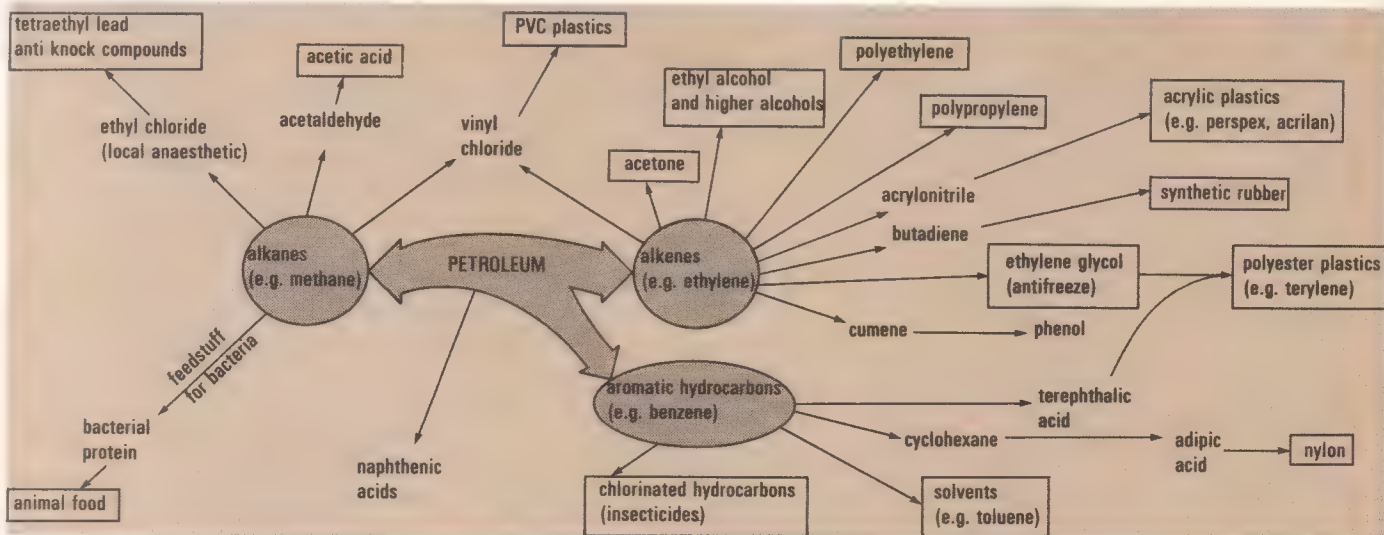
smelling organic sulphur compounds are added, so that leaks can be detected.

Natural gas consists mostly of methane, which makes up 65–90 per cent of the gas, depending on its origin. A few higher hydrocarbons are also present, together with small amounts of helium, carbon dioxide, nitrogen and hydrogen sulphide.

Natural gas is used as a major source of some chemicals. The methane in the gas is converted to methyl alcohol. Other hydrocarbons that can be isolated from natural gas are acetylene, butane and propane. Acetylene is used in the process of making nitrile rubbers. Propane and butane are also used as fuels. They are usually compressed into small portable containers, and in this form are called *bottled gas*. In some parts of the world the butane content of natural gas is extremely high. Where this occurs, it is extracted and used in the manufacture of butadiene rubbers. Other chemicals extracted from natural gas include helium (in the USA), which makes up two per cent of the content, and sulphur. The natural gas produced at Lacq in France contains 15 per cent hydrogen sulphide, and is one of the world's major sources of sulphur.

Crude petroleum is distilled in fractionating columns (above left) into six main fractions (above right). The lightest molecules, those of the gas, gasoline and naphtha fractions, are removed at the top of the fractionating column and separated in a later process. The bubble caps allow the lighter petroleum vapours to rise up the columns and condense. The condensing liquids can also flow down the tower via interconnecting pipes. When the process has stabilized, the fractions can be removed from the various levels of the tower.

Below: Examples of petrochemical products.





Organic halogen compounds have many uses. Some chlorine compounds are used as pesticides and sprayed on crops (left). Gases that contain chlorine



Versatile Halogen Compounds

The list of important uses for organic halogen compounds is a long one. The majority of these compounds contain chlorine, either by itself or with another halogen. But fluorine, bromine and iodine also form a wide range of compounds.

Many chlorine compounds are used as solvents. Of these, *trichlorethylene* is the most widely used. Chlorine is also found in the plastic PVC (*polyvinyl chloride*). Several organic drugs contain chlorine, as do some of the World War I gases. Chlorine compounds are also used as weedkillers and insecticides.

Fluorine compounds have many applications in modern society. Early refrigerators

used ammonia as the refrigerant. Nowadays, organic fluorine compounds known as *freons* are used. Fluorine compounds are also used in aerosols as propellant gases. Fluorine also forms part of the plastic material known as Teflon used in many non-stick pans.

Iodine and bromine compounds are mostly used in organic chemistry. Many halogen compounds are used as intermediates for synthesizing other organic compounds. Among the most useful of these intermediates are Grignard reagents. These compounds take their name from Professor Victor Grignard of Lyons, who first prepared them in the 1900s. He received a Nobel Prize in 1912.

Organic halogen compounds called fluorochloro-hydrocarbons, or Freons, are often used as propellants in commercial aerosols.

Refrigerants and Solvents

Fluorine is the most reactive of all the elements, consequently its compounds tend to be stable. The fluorinated refrigerants and aerosol propellants are no exception; they can be regarded as deriving from methane, CH_4 , and usually contain a second halogen. Examples are CCl_3F (Freon 11) and CBrF_3 (Freon 13.B1).

Chlorine derivatives of methane form a useful and varied series: CH_3Cl , methyl chloride, is a synthesis chemical; methylene chloride, CH_2Cl_2 , has uses in paint removers and photographic film; chloroform, CHCl_3 , is a solvent (it is far too poisonous to be used nowadays as an anaesthetic) and carbon tetrachloride, CCl_4 , is a very stable solvent and degreasing liquid.

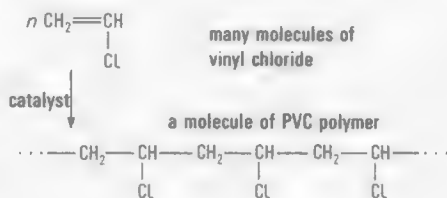
Trichlorethylene, $\text{CHCl}=\text{CCl}_2$, is used for dry-cleaning and industrial degreasing, where its non-flammability and low toxicity make it one of the safest of solvents.

Carbon tetrafluoride, CF_4 , is an extremely

unreactive liquid, which, like several other alkyl halogen compounds, is used in fire extinguishers. Among other remarkable halides is methylene iodide, CH_2I_2 , which after mercury is the heaviest of all liquids; it is used by geologists to separate minerals by their density.

Halogens and Polymers

Vinyl chloride, $\text{CH}_2=\text{CHCl}$, and vinylidene chloride, $\text{CH}_2=\text{CCl}_2$, are important monomers for the manufacture of vinyl plastics and synthetic fibres. Vinyl chloride polymerizes as follows:



compounds were used in World War I (below). Carbon tetrafluoride is used in some fire extinguishers (right), because it is extremely unreactive.



Ethylene tetrafluoride, $F_2C=CF_2$, is the monomer of the non-stick, temperature resistant plastics material known as PTFE, Fluon, or Teflon. Among other important halogen monomers is chloroprene, $CH_2=CHCl-CH_2$, which polymerizes to the synthetic rubber known as neoprene, used in applications which require resistance to oils and solvents.

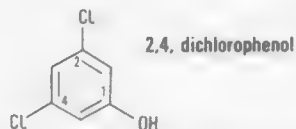
Drugs and War Gases

Ethyl chloride, CH_3CH_2Cl , is a well-known 'skin freezing' local anaesthetic. Iodoform, CHI_3 , is much safer compound than its analogue chloroform, is a very useful antiseptic. Chloral, CCl_3-CHO , is the basis of the hypnotic drug chloral hydrate, also known as 'knockout drops'.

By contrast with these largely beneficial substances, phosgene, $COCl_2$, is a lethal gas used in World War I. Another such is mustard gas, $(C_2H_4Cl)_2S$. Chloropicrin, CCl_3NO_2 , confers mixed benefits: it is a tear gas but is also a useful insecticide and fumigant.

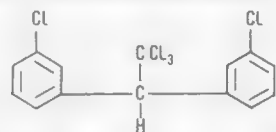
Weedkillers and Pesticides

Three of the most important modern weedkillers are chlorine compounds. They all have long chemical names but are familiar to gardeners as 2,4-D, 2,4,5-T and MCPA, and are derived from 2,4, dichlorophenol:



Many other chlorinated hydrocarbon weedkillers are marketed.

The insecticide DDT is a heavily chlorinated compound containing two aromatic rings:

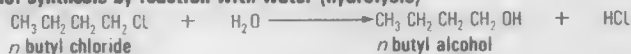


DDT (dichloro diphenyl trichloroethane)

Other chlorinated hydrocarbon insecticides include TDE, methoxychlor, aldrin, dieldrin and BHC.

SYNTHESIS OF COMPOUNDS USING HALOGEN INTERMEDIATES

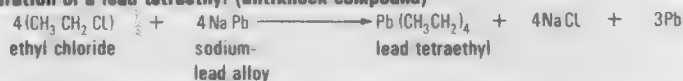
Alcohol synthesis by reaction with water (hydrolysis)



Preparation of an alkene



Preparation of a lead tetraethyl (antiknock compound)



Halogen Intermediates

Organic chemists appreciate halogen compounds as among the most useful for the synthesis of alcohols, esters, ethers, nitriles, amines and many other organics. The full range of these syntheses is much too wide to be covered fully here, but some indication of the versatility can be given by the three examples shown above.

Grignard reagents are organic compounds that contain halogens and magnesium. They

have the general formula $R-Mg-Hal$, where R is an aliphatic or a cyclic group.

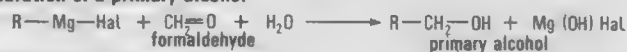
Grignard reagents are the most usefully versatile of all organic halogen compounds, and are used not only for laboratory syntheses but also for the preparation in bulk of many organic chemicals. Alkanes, alcohols, aldehydes, ketones, carboxylic acids, naphthalenes and silicones can all be prepared using Grignard reagents. Some examples of these preparations are shown below.

SYNTHESIS OF COMPOUNDS USING GRIGNARD REAGENTS

Preparation of an alkane



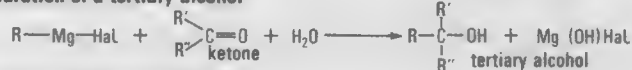
Preparation of a primary alcohol



Preparation of a secondary alcohol



Preparation of a tertiary alcohol



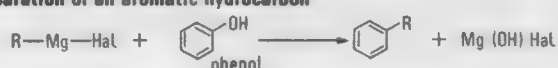
Preparation of a carboxylic acid



Preparation of phenol



Preparation of an aromatic hydrocarbon



Polymers and Plastics

Polymers are compounds that have very long molecules. Each molecule is made up of a number of smaller molecules (*monomers*) of a simple compound. For example, the monomer ethylene, $\text{CH}_2=\text{CH}_2$, can polymerize to form polyethylene, $\dots\text{-CH}_2\text{-CH}_2\text{-CH}_2\text{-CH}_2\text{-CH}_2\text{-CH}_2\dots$

Natural Polymers

Polymers that occur naturally include the starchy and cellulose tissues of plants (see page 243) and the proteins and nucleic acids of both animal and plant tissues (see page 264). Cotton and linen are natural cellulose fibres used in the textile industry. But cellulose fibres from wood are also used to make synthetic fibres, such as rayons. Another natural polymer that is widely used by man is rubber. The monomer of natural rubber is isoprene, $\text{CH}_2=\text{C}(\text{CH}_3)-\text{CH}=\text{CH}_2$. This polymerizes naturally inside the rubber tree to form a latex. After being tapped from the tree, the

Perspex, an acrylic polymer, has the advantage of being transparent. This perspex 'egg' contains sensitive electronic equipment. It is used to test the processes through which eggs pass. When subjected to the same treatment as ordinary eggs, the perspex imitation registers knocks that might break eggshells and a small light comes on inside the egg.

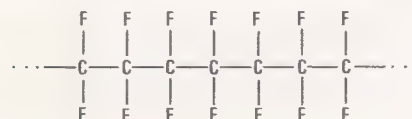


latex is treated to remove impurities, and then dried and processed to make 'rubber'. Rubber stretches easily because its long polymer molecules slide over each other. During *vulcanization* cross-links are formed between the molecules, and the rubber becomes springier and less sticky (see page 240).

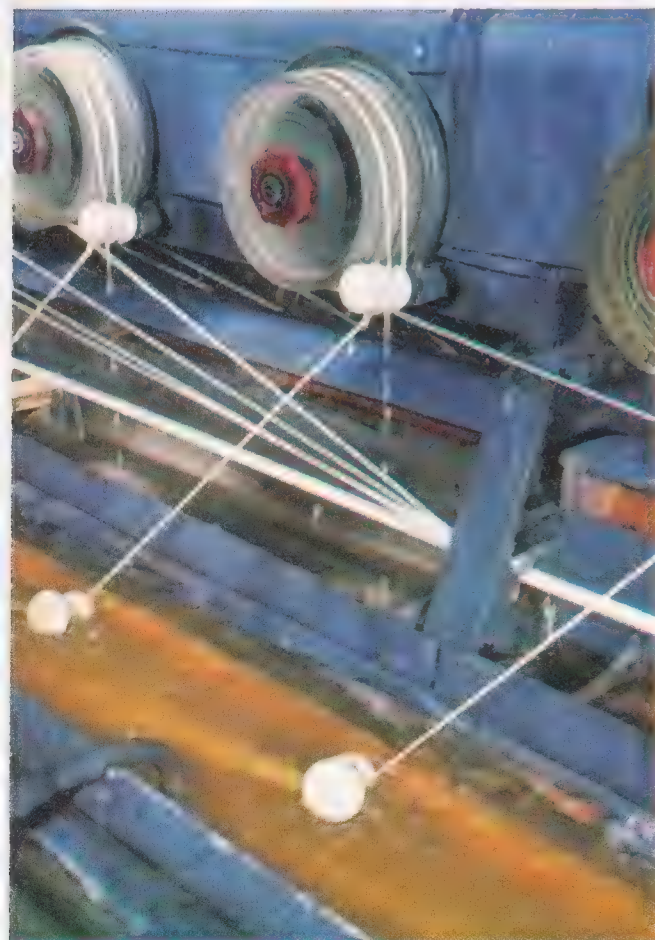
Man-made Polymers

A large number of synthetic polymers are now available. In addition to natural rubber, there are several kinds of synthetic rubber. The name 'plastics' is given to the wide variety of man-made polymers that can be moulded into required shapes. Plastics can be divided into two groups: *thermoplastics* and *thermosetting resins*. Thermoplastics best deserve the name 'plastics' because when they are squashed or bent, they distort in a *plastic* way, and recover their shape only partly. This distinguishes them from rubbers which behave *elastically*. Thermoplastics are all *linear* polymers, that is, they consist of long-chain molecules. Thermosetting resins contain three-dimensional networks of molecules and, unlike thermoplastics, cannot be softened and remoulded.

Thermoplastics are widely used to make bowls, buckets and piping. They include polyethylene, polypropylene and polyvinyl chloride or PVC (see page 248). Polytetrafluoroethylene or PTFE has the formula




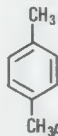
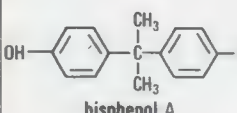
Filaments of viscose rayon, made from the natural polymer cellulose, leaving the acid bath. In the process of making viscose rayon, wood pulp is first steeped in caustic soda, pressed damp dry, and ground up to a form resembling breadcrumbs. This is then reacted with carbon bisulphide to form cellulose xanthate, which is dissolved in diluted caustic soda to form viscose. This is forced through tiny holes in a 'jet' immersed in an acid bath to form filaments of viscose rayon yarn. From the acid bath, the filaments pass up round a rotating wheel, and then down to join all the fibres from the other jets in a 'tow' (on the right hand side of the picture).



The strong carbon-fluorine bonds of this polymer make it stable to heat and chemicals, and non-sticky, an ideal combination of properties for its main use as a non-stick pan liner.

Acrylic polymers are most familiar to us as the transparent material called Perspex, but other acrylics are used in paints, lacquers and rubber. Another glasslike thermoplastics resin is polystyrene, familiar as a rigid plastics foam, often used for ceiling tiles and packaging. Flexible foams are also synthetic polymers: those used nowadays to stuff furniture are mostly polyurethanes—plastics which can equally be considered as types of rubber.

Thermoplastics are used on a huge scale to make fabrics, especially nylon and polyesters. Chemically, nylon is a complex polyamide, its molecules containing the amide group $\text{CO}-\text{NH}$. Nylons are among the strongest of plastics: weight for weight they can have a tensile (stretched) strength greater than that of steel, a quality invaluable in nylon fishing

EXAMPLES OF THERMOPLASTIC POLYMERS	
monomers	polymers and some of their applications
$\text{CH}_2=\text{C}(\text{CH}_3)\text{COOCH}_3$ methyl methacrylate	transparent polyacrylates (Perspex)
$\text{CH}=\text{CH}_2$  styrene	Polystyrene (foam tiles) $\cdots\text{CH}(\text{C}_6\text{H}_5)\text{CH}_2\text{CH}(\text{C}_6\text{H}_5)\text{CH}_2\text{CH}(\text{C}_6\text{H}_5)\cdots$
 and $\text{CH}_2=\text{CH}_2$ ethylene	Terylene (clothing) $\cdots\text{O}-\text{C}(=\text{O})-\text{C}_6\text{H}_4-\text{C}(=\text{O})-\text{O}-\text{CH}_2\text{CH}_2\cdots$ ester group
 and $\text{Cl}-\text{C}(=\text{O})-\text{Cl}$ phosgene	polycarbonate resin (electrical plugs and sockets) $\cdots\text{O}-\text{C}_6\text{H}_4-\text{C}(\text{CH}_3)_2-\text{C}_6\text{H}_4-\text{OC}(=\text{O})\cdots$



qualities for cements and coatings: these include the epoxy resins and some polyurethanes (here behaving as thermosets rather than thermoplastics or rubber).

Somewhat resembling Bakelite (a phenol-formaldehyde resin) are urea-formaldehyde and melamine formaldehyde resins. Among their applications are kitchen worktops.

Synthetic Rubber


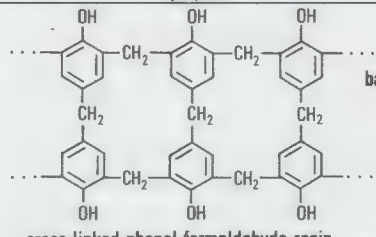
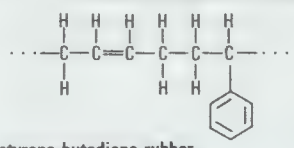
Synthetic rubber monomers also polymerize to *latices*, and, like natural rubber, they can be hardened by vulcanization. Styrene-butadiene rubber, or SBR is the rubber most often used for tyres. Neoprene, or polychloroprene, is used to make chemical-resistant hose.

Left: Some applications of man-made plastics. Most of these are thermoplastics, such as polythene (polyethylene) and polypropylene. The formica table on which the articles are placed is a thermosetting plastic.

lines and tow ropes. Polyesters contain an ester group, the most well-known polyester being perhaps Terylene. Among other important thermoplastics are polycarbonates, hard, impact-resistant polymers with high softening temperatures.

Among the first plastics to be developed was Bakelite, a type of thermosetting resin which has been used for over half a century for electrical connectors. Bakelite is made by the *copolymerization* of phenol and formaldehyde, which react in the presence of a catalyst to form a highly cross-linked network. This cross-linkage makes Bakelite a hard, rigid material with high electrical resistance. When heated strongly it does not melt but breaks down; it is thus a typical thermoset.

Other thermosets possess great strength and resistance to chemical attack, ideal

EXAMPLE OF HIGHLY CROSS-LINKED THERMOSETTING RESIN	
monomers	polymer
 and $\text{H}-\text{C}(=\text{O})-\text{H}$ formaldehyde	 bakelite cross-linked phenol-formaldehyde resin
EXAMPLE OF A SYNTHETIC RUBBER	
monomers	elastomer (rubber-like polymer)
$\text{H}_2\text{C}=\text{CH}-\text{CH}=\text{CH}_2$ butadiene and $\text{C}_6\text{H}_5-\text{CH}=\text{CH}_2$ styrene	 styrene-butadiene rubber (SBR) tyres

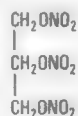


Explosives and Dyes

An explosive is a substance that, when it burns, gives off large amounts of gas, heat and light. The expansion of the gas causes the blast of the explosion. Dyes are used for colouring materials. Although these two types of substance would seem to have nothing in common, nearly all the dyes and explosives in these two groups are, in fact, organic nitrogen compounds. The molecules of these compounds contain nitrogen groups that react very easily. This accounts for the fact that the explosives explode and the dyes cause colour changes. Picric acid is an example of a compound that will even do both—it is a yellow dye and is also an explosive.

Nitrogen Explosives

Certain inorganic nitrogen compounds, for example nitrogen trichloride, NCl_3 , explode readily and violently. Nitroglycerine, which has the formula



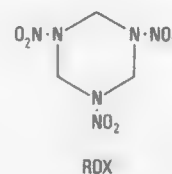
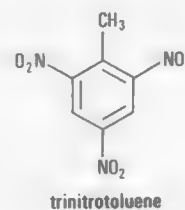
was once used alone as an industrial explosive. It, too, is very liable to explode 'at the drop of a hat' and is nowadays used only in the form of dynamite, where it is mixed with inert materials.

Modern organic nitrogen explosives—dynamite included—are less dangerously unstable and require a detonator to be exploded. Characteristically, the detonator also contains a nitrogen explosive, usually mercury fulminate or lead azide, $\text{Pb}(\text{N}_3)_2$.

Like glycerine, toluene can be heavily nitrated to make a high explosive, in this case trinitrotoluene or TNT. Even more powerful than TNT is an explosive known as RDX or cyclonite which was widely used in World War II. It contains still more nitrogen. More energy is stored in RDX than in almost any other chemical compound. But more violent explosions still are obtained when aluminium powder is added to the explosive; this oxidizes to release more heat.

Other important nitrogenous high explosives include PETN, Tetryl, ammonium nitrate, nitrocellulose (guncotton) and, of

Forms of explosive for quarrying and blasting must be safe to handle. They are usually nitroglycerin mixed with another material. Dynamite is nitroglycerin mixed with kieselguhr, and absorbent material. Gelignite is a mixture of nitroglycerin, nitrocellulose, sodium nitrate and wood pulp. Blasting gelatin is one of the most powerful commercial explosives and consists of nitroglycerin and guncotton.





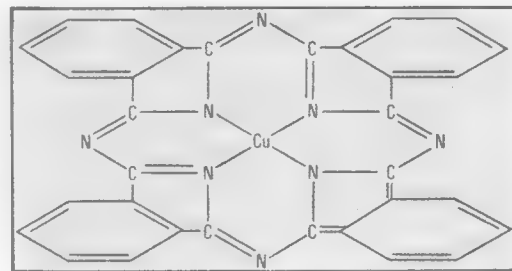
course, gunpowder, which contains potassium nitrate.

High energy nitrogen compounds have also been used as fuels to propel rockets, when they are burned at a controlled rate, not exploded. Unlikely as it seems, even nitroglycerine can be used in this way.

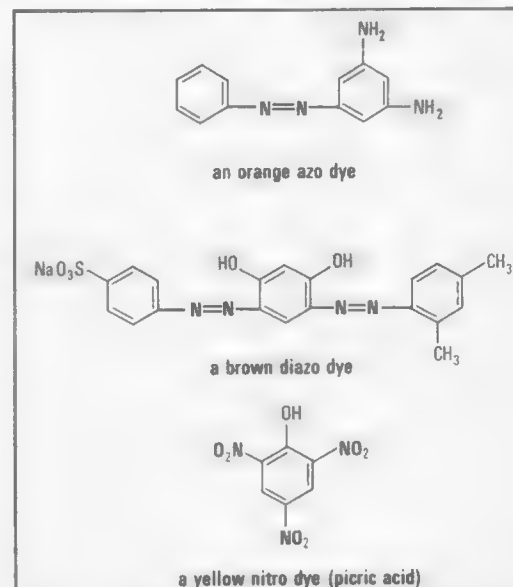
Nitrogen Dyes

People dyed their clothes (and bodies!) from prehistoric times using pigments obtained usually from plants. The first synthetic dye, *mauvein*, was made in 1856 by the British chemist William Perkin, who used the nitrogen compound aniline as his starting material. Since Perkin's time hundreds of different dyes containing nitrogen groups have been made artificially, particularly from aromatic coal tar chemicals. Most numerous of these are the azo dyes, so called because they contain nitrogen as the azo group, $-N=N-$. This group is an example of a *chromophore*, associated with colour in pigments and dyes. Other nitrogen chromophores are the nitro ($-NO_2$), nitroso ($-N=O$) and cyano ($-C\equiv N$) groups. A dye, by the way, can be described as any pigment that will stick to fibrous materials so as to colour them more or less permanently. A dye will therefore have not

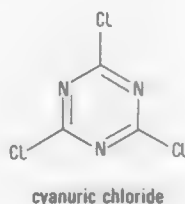
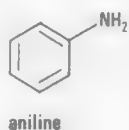
Right: A phthalocyanine dye has a molecule very like that of the blood pigment haemoglobin. The metal atom at the centre of the haemoglobin pigment is iron (Fe), whereas that of the dye is copper (Cu), as shown here. Chlorophyll, the green pigment of plants, also has this type of structure, but its central atom is magnesium (Mg). This important chromophore is known as a porphyrin structure.



Left: RDX is the explosive used in naval guns to propel the shells.



Right: Three dyes showing the colour groups (**bold letters**), and the reactive groups that stick the dyes to the fabric (grey tints).

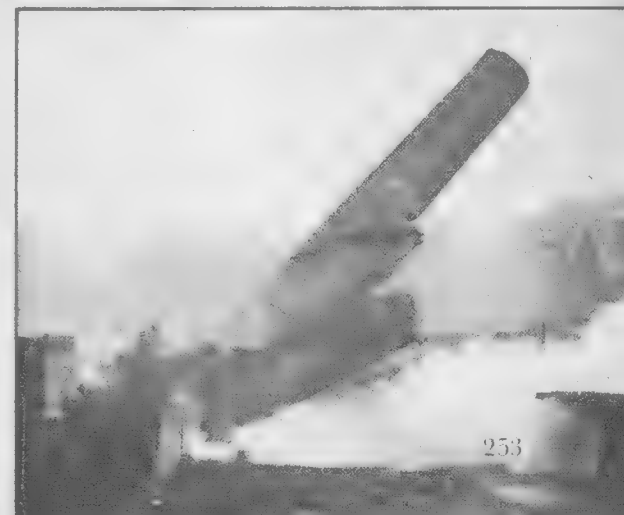


only a chromophore but also a 'sticky' group, which attaches itself to the material.

Another type of nitrogen dye is remarkable in that its structure is very similar to that of haemoglobin, the animal blood pigment. These dyes are used to colour paper and synthetic polymers.

In dyeing natural fabrics, the addition of a *mordant* such as a chromium compound is often necessary to help fix the dye to the fibres. Synthetic fibres such as nylon and polyesters also resist unassisted dyeing. Certain modern dyes, however, become permanently fixed to either natural or synthetic fibres by direct chemical reaction with their polymer molecules. For this reason they are known as *reactive dyes*. Some of these dyes are based upon the nitrogenous compound cyanuric chloride.

An old factory chimney being demolished. The amount of explosive is accurately judged and carefully placed at the base. The chimney therefore falls in the required direction, and the minimum of damage is done to the surrounding area.





Above: The predominant colour of the countryside is green. This is due to the chlorophyll pigment contained in the chloroplasts of the leaves of most plants.

Nature's Colours

When we think of the colours, of nature, the one that first springs to mind is green, the colour of grass and leaves. But autumn leaves change colour, turning into bright yellow, red or brown. The colour of a tree's bark and of roots does not change markedly during the year from dullish yellows and browns. By contrast, the coat of a northern mammal such as a stoat can lose all its colour in winter, while we darken in colour when we lie in the sun. Flower petals have colours that appear nowhere else in nature, although some animals, such as the mandrill, and certain insects, birds and sea creatures are also very brightly coloured. What, then are the pigments that cause these various natural colours?

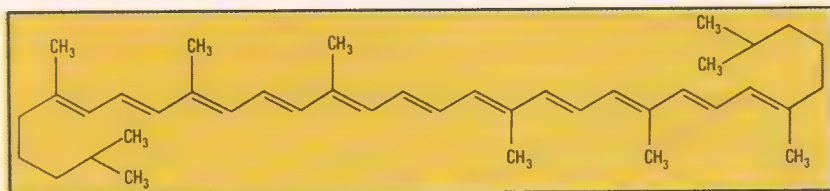
Chlorophyll

The green of nature comes from the pigment chlorophyll which has the *porphyrin* structure also seen in the haemoglobin molecule and in some dyes (see page 253). The chlorophyll molecule has a magnesium atom at its centre, explaining a plant's need of this metal in the form of soil minerals.

Chlorophyll is necessary for *photosynthesis*, the chemical process in green plants by which

Below: Butterflies, such as this purple emperor, often have extremely bright colours. In this case the white, and the small areas of purplish blue are due to *iridescence*—the reflection of light in the scales of the wings. The remaining colours are all due to different pigments.





Above: The structure of a molecule of carotene, an orange pigment that helps to give the colour to autumn leaves.



Left: The flower of the New Guinea creeper. Reds are common colours for flowers, and are generally due to pigments called anthocyanins.

Above right: Yellow butterflies get their colour from pigments called pterins.

Below: In the autumn, leaves turn brown and yellow. These colours are due to carotenes and xanthophylls.

Autumn Colours

Before deciduous plants shed their leaves in autumn the chlorophyll breaks down, so revealing other pigments that had been masked by the green pigment.

The bright yellows and reds of autumnal leaves are the carotenes and xanthophylls, pigments which help chlorophyll in photosynthesis, but which the plant easily makes

carbon dioxide from the air, together with water, is built up into more complex compounds. From these compounds, the plant makes cellulose, starch, lignin and many other substances. Photosynthesis also requires the energy of sunlight; it can be shown as



The chlorophyll in this reactions behaves rather like a catalyst; it is not used up. There are several kinds of chlorophyll which differ in their sensitivity to light of particular wavelengths. For example, red seaweeds, the plants that live deepest in water, have a chlorophyll that is most sensitive to light of long wavelengths, which best penetrates water. Red seaweeds have another pigment, phycobilin, which is also sensitive to this light.



Many insects are brightly coloured. The warning coloration of the stink bug (left) indicates to would-be predators that the insect is inedible. Wasps also show warning coloration, but the hoverfly (right) is harmless. It mimics the colours of the wasp and gains protection from would-be predators.





afresh. The same pigments account for the colours of ripe fruits such as tomatoes and some root vegetables such as carrots.

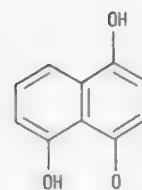
Flower Colours

The earliest dyes used by man included flower colours such as yellow saffron from crocuses (indigo, the ancient violet-blue woad dye, came from leaves not flowers). The colours of flowers are generally those of anthocyanins, pigments which range in colour from blues to reds to violet. Chemically, anthocyanins are very complex, being composed of sugars and attached groups; these groups are typical of certain flower colours and some are named after the flowers; for example, pelargonidin and delphinidin.

Duller plant colours are generally due to quinones, having one or more rings.

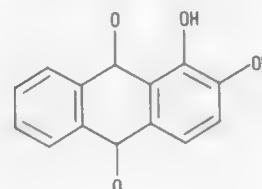
Above: The girl on the left has freckles. These are due to localized collections of melanin. The girl on the right has no freckles, but even so melanin is present in her skin. If she exposes her skin to the ultraviolet radiation of the sun for some time, the amount of melanin in her skin will increase, to protect her from the radiation.

Below: Negroes generally have a considerable amount of melanin in their skin (left). This is an adaptation to their surroundings, and affords protection from the strong solar radiation that occurs near the equator. However, occasionally people are born without melanin. Such people are known as albinos (right).



juglone, a quinone in walnut shells

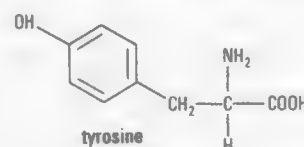
These yellow or brown pigments of stems, tubers, roots and fruit shells are the most common in nature, although we usually hardly notice them. A few quinones, such as the anthraquinone alizarin, have bright colours.



alizarin, a deep red dye

Melanin

Compared with plants, animals have relatively few pigments. One group of black and brown pigments, collectively called melanin, is much the most common and is found in animals from man and other mammals to squids and worms. How dark, or light, or dark and light in patches these various animals are, depends largely on the amount of melanin in the skin. Exposure to sunlight forms melanin in the skin, so turning it brown. Hair colour is also due to this pigment. The structure of the melanin molecule(s) is very complex but the pigment is formed in the human body from tyrosine, one of the amino acids that also build up into proteins.

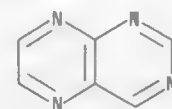


tyrosine

Other Animal Colours

Some yellow and red animal colours are those of carotene-like pigments and a few blue animal pigments also contain carotene, but together with a protein.

Pterins are pigments that contain the pteridine group.



pteridine

Pterins give yellow colours to some butterflies, red and yellow colours to the skins of fishes, and purplish colours to their eyes.

Many brilliant colours in the animal world are not produced by pigments at all. The iridescent colours of a bird's feathers or the scintillating colours of some tropical fishes and squids, for example, are caused by refraction and interference of light in feathers, scales and skin crystals.

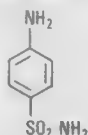
Drugs and Hormones



Colonies of *Streptomyces*, a group of soil bacteria. From these bacteria, pharmacists can extract streptomycin, which is an effective antibiotic drug.

Sulpha Drugs

The ancestor of the sulpha drugs is a red dye called Prontosil, which, a chemist noticed, acted against bacteria. A related compound, sulphanilamide, was the first sulpha drug.



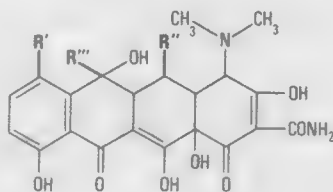
But other even more effective sulpha drugs followed, including sulphapyridine, sulphathiazole and sulphadiazine. Between the two world wars, these drugs revolutionized the treatment of diseases caused by bacteria, saving the lives of thousands of people. They have the disadvantage of being more or less toxic (poisonous) to the kidneys, although later sulpha drugs, such as sulphadiazine, are less so.

Antibiotics

Like sulpha drugs, antibiotics act against infections by bacteria and other microbes, but unlike them they occur in nature. They are produced by certain bacteria and moulds as substances which are *anti-biotic*, that is, which act against rival organisms.

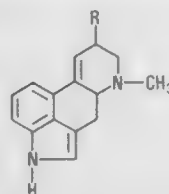
The first antibiotic, penicillin, was discovered by Alexander Fleming in 1928 and was first made on a large scale during World War II. Penicillin is non-toxic to most people, and is so effective against many diseases that it is truly a 'miracle' drug.

Even so, many other disease microbes are completely unaffected by penicillin. Today



A molecule of a tetracycline antibiotic, as its name implies, has four rings. The R groups differ in various tetracyclines.

The molecule of LSD. The R group includes amides.



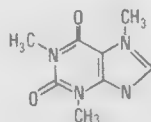
these diseases can nearly always be attacked successfully by other antibiotics such as streptomycin and the tetracyclines. These, and several other antibiotics, are produced in nature by *streptomycetes*, advanced kinds of bacteria that live in soil. Chemically, streptomycin is very complex, containing amine and glucosamine groups. Tetracyclines are so called because they have a molecular structure containing four rings.

Very few microbes can withstand modern drug treatment involving one or more antibiotics together, perhaps, with sulpha drugs. *Viruses*, however, are often unaffected by these or most other drugs. So virus diseases, like bacterial diseases fifty years ago, remain to be conquered.

Alkaloids

Alkaloids are drugs usually extracted from plants, many of which are also strong poisons. For example, opium from poppies is a mixture of about 20 alkaloids. These drugs all contain nitrogen as amine groups, explaining why their names end in *-ine*, as caffeine (from tea and coffee), morphine (from opium), atropine (from deadly nightshade) and nicotine (from tobacco).

Quinine, extracted from the bark of the cinchona tree, is one of the less toxic alkaloids and has helped millions of sufferers from malaria. Other alkaloids, including caffeine, act by stimulating the nervous system. But many alkaloids are especially dangerous drugs because they are addictive, always causing great misery and sometimes death to



The chemical structure of the alkaloid caffeine, found in tea and coffee.

Two thousand years ago, Chinese doctors knew of many hundreds of drugs, which they extracted mainly from plants. By medieval times Chinese drug books, or *pharmacopoeias*, contained thousands of drug prescriptions. The action of many of these drugs on the human body was described, but not the chemical structure of any drug, because the science of chemistry was too little developed.

Nowadays, organic chemists are usually able to discover and describe the chemical structure of any extract from plants or animals which has pharmacological activity, that is, which behaves as a drug.

Having done this, chemists can then make related compounds artificially. The semi-synthetic penicillins are one example: here the chemist 'tailors' the natural molecule of penicillin to make many other useful drugs. Chemists can also make drugs which have no 'medical relations' in nature. Examples are the sulpha drugs.

people who become dependent on them. These addictive alkaloids include morphine (carefully prescribed by doctors as a pain-killer) and its even more addictive relative heroin, and, of course, opium itself.

Codeine, which is also an opium alkaloid, is not particularly addictive and is useful as a minor painkiller.

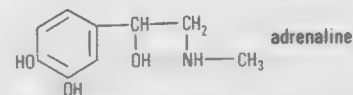
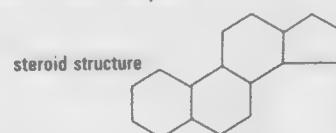
Some Other Drugs

Among numerous other organic compounds which can be called drugs because they affect our bodies in useful ways, are the salicylates which include aspirin and the ingredients of many cold and 'flu powders. These drugs are called antipyretics because they lower body temperature, although after a hundred years of aspirin, scientists still do not know exactly how!

Psychotropic drugs such as mescaline and LSD affect the working of the brain and so change a person's behaviour. Often thought of as modern drugs, many have in fact been used for thousands of years by medicine-men to produce states of 'holy intoxication'. Doctors now use them to investigate and treat some kinds of mental illness.

Hormones

Hormones are substances produced in the bodies of animals by their endocrine glands. Many of them are now made artificially and used as drugs, particularly in the treatment of rheumatic diseases. Hormones affect and control growth and many kinds of activity in the body; most have a typical *steroid* structure but some, such as adrenaline, have molecules of other shapes.



Most hormones have a steroid structure, but the structure of adrenaline is completely different.

Food and Vitamins



Herbivorous animals, such as cattle, are able to digest the cellulose material of plants. This together with proteins, minerals, and vitamins, supply the animal with the chemicals it needs for growth and energy. When the herbivore is itself killed and eaten, the chemicals that it has built up from its food are used by the predator for its own energy and growth.

What is Vital in Diets

Our diets must provide us with certain chemical elements in large quantities. These elements are carbon, hydrogen, oxygen, nitrogen, sulphur and phosphorus. Proteins, which occur mainly in meat, fish, milk and cheese, supply us with all these elements. Fats (butter, milk, cheese) and carbohydrate foods (sugar, potatoes, rice, bread) supply mainly carbon, hydrogen and oxygen. Also vital to us, but in smaller amounts, are the vitamins, without which we suffer from certain *deficiency diseases*.

Many foods also contain iron (which we need in fairly substantial amounts, mainly for the haemoglobin of blood), calcium (for bones and teeth), and sodium, potassium and chloride, which, together with phosphate, are the chief inorganic ions in the chemical reactions of the body.

Finally, our diets must provide us with very small quantities of other elements, which for this reason are known as *trace elements*. These include the metals copper, zinc, magnesium, cobalt and molybdenum, which, together with the vitamins, assist in the work of the enzymes, the catalysts which make possible most of the chemical, or *metabolic*, reactions of the body. Non-metallic trace elements include iodine, which occurs in the molecule of the thyroid hormone, and fluorine, which is normally present in teeth.

VITAMINS

Vitamin	Chief source	Needed for
Vitamin A	Carotene (which body can convert to Vit. A) in carrots, egg yolks, butter, yellow or orange fruits, vegetables	growth; prevention of dry skin; formation of visual purple, which aids vision in dim light; lack of Vit. A can lead to atrophy of white of eyeball
Vitamin B₁ (thiamine)	wheat germ, bread, pork, liver, potatoes, milk	prevention of beri-beri
Vitamin B₂ (riboflavine)	milk, eggs, liver	lack may result in skin disorders, inflammation of tongue, and cracked lips
Nicotinic acid (niacin)	yeast, liver, bread, wheat germ, kidney, milk	prevention of pellagra
Vitamin B₆ (pyridoxine)	meat, fish, milk, yeast	lack can lead to convulsions in babies or anaemia in adults
Vitamin B₁₂ (cyanocobalamin)	liver, kidney, eggs, fish	formation of red blood cells; healthy nerve tissue
Vitamin C	fresh fruit and vegetables	prevention of scurvy
Vitamin D	margarine, fish, oils, eggs, butter; also formed in skin exposed to sunlight	formation of bones; lack causes rickets in children
Vitamin E	most foods	little known
Vitamin K	green vegetables; also formed by bacteria in intestine	clotting of blood

HOW WE DIGEST FOOD

After meals, food in our bodies is broken down to simpler materials which can be assimilated, or taken into the bloodstream and used by the body as necessary. The process of breaking down and absorbing food is called digestion. Some substances in our food, particularly many fibrous materials, are not digested and pass straight along the digestive canal and out.

Proteins are first broken down in the stomach, by enzymes and hydrochloric acid, to *polypeptides* and finally, by other enzymes in the intestine, into their unit, or monomer, compounds. These are the *amino acids*, which are assimilated by the body, among other things for building other proteins. Proteins contain about twenty kinds of amino acids, but we need only eight of them—the *essential amino acids*—in our diet. The

body can make the others. (See page 265.)

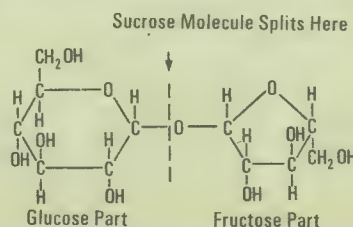
Starch, and the few other polysaccharides that we can digest (cellulose, for example, we cannot) are broken down by enzymes in saliva, the pancreas and the intestine into monosaccharides such as the sugar glucose. Ordinary table sugar (sucrose) is split by enzymes into glucose and fructose. Glucose is the readiest source of energy in the body.

It provides all its energy only after many metabolic reactions, but the overall effect is the same as burning the sugar:



If the body does not need energy, glucose is built up to the starch-like polymer glycogen, which is stored in the liver and muscles.

Fats are not broken down chemically in the stomach, but are churned with the rest of the food into small particles, and in the intestine are *emulsified* into very small droplets with the help of bile from the gall bladder. Enzymes also split up fats to some extent into fatty acids and simpler glycerides. Eventually the emulsified fat droplets are small enough to be absorbed by the intestine, from which they reach the bloodstream.



The Science of Life

Two simple multicellular organisms. Several hydras, small animals that belong to the coelenterate group, are sitting on a green alga, a simple plant that can be found in most freshwater ponds and streams.



The Living Cell

All living things are made of cells. A cell is like a tiny industrial estate, which orders, manufactures, packages and despatches a large and varied range of chemical substances. All these processes are controlled by the genetic material contained in the cell.

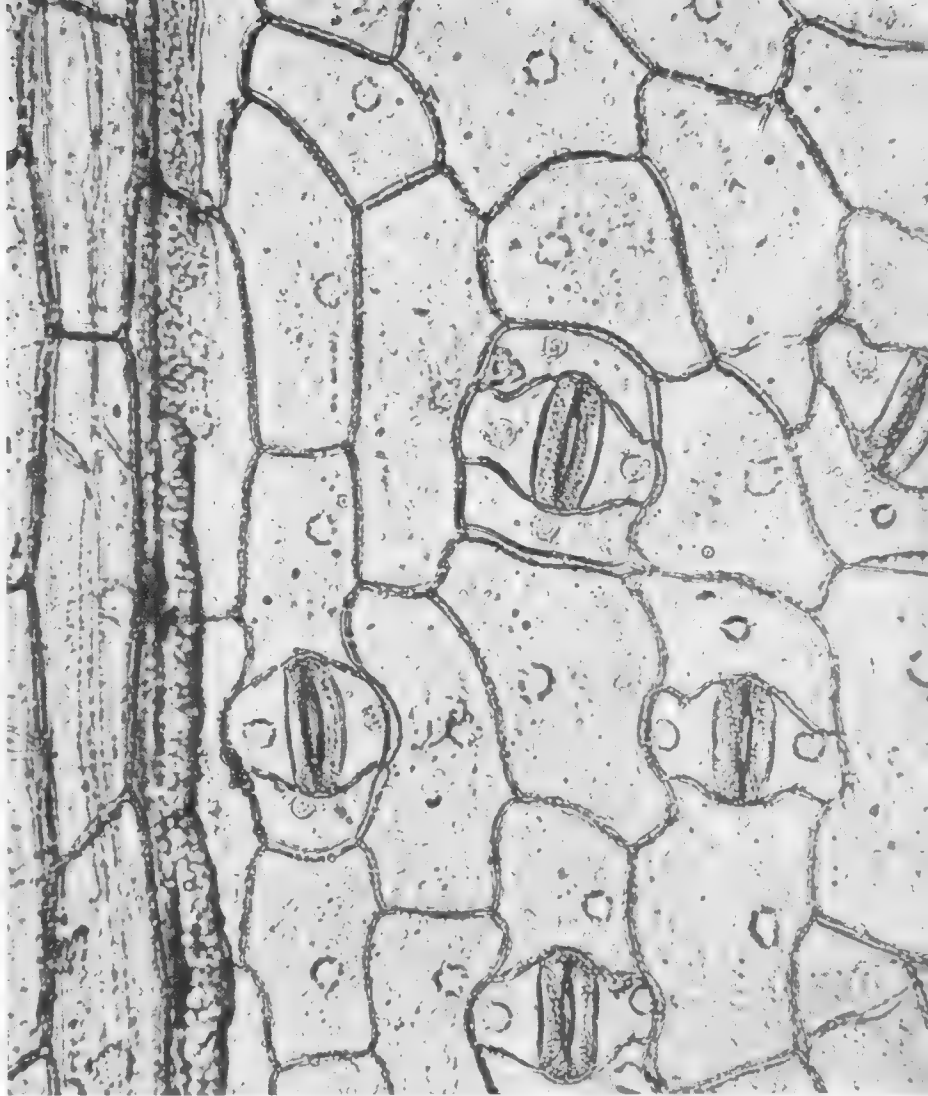
Each single cell is a clearly defined unit, bounded by a membrane that separates it from other cells or the outside environment. Some plants and animals consist of only a single cell. Others are composed of billions of cells. The shapes and sizes of cells vary considerably, depending on their function. The more complex the animal or plant, the more the structures and functions of cells vary. In humans, for example, different types of cell make up the tissues of specialized organs such as the brain, bone, liver and kidneys. But whatever their function, they all operate in much the same way; they take in food substances and oxygen, process them to produce energy, and expel waste products. The energy-producing chemical processes that occur within an organism are collectively called its *metabolism*. The substances that are taken in are referred to as *metabolites*. The types and amounts of metabolites absorbed by a cell vary greatly depending on its function. But, taken as a whole, the metabolic activity of the cells supply the organism with its requirements for growth, reproduction, repair of worn-out tissues, and disposal of wastes, as well as its energy needs for movement.

The cells of animals, plants and most micro-organisms are similar in their basic structure. They consist of a jelly-like, watery material called cytoplasm contained in a cellular membrane. Most of them have a clearly defined nucleus surrounded by a nuclear membrane. Cells with a nucleus are called *eucaryotic cells*. Those without a nucleus are known as *procaryotic cells*. The cellular membrane surrounding each cell not only contains the cytoplasm of the cell, but also regulates the types and quantities of substances entering and leaving the cell.

Within the cytoplasm of the eucaryotic cell are a number of organelles, structures that perform particular functions and contain specialized membranes.

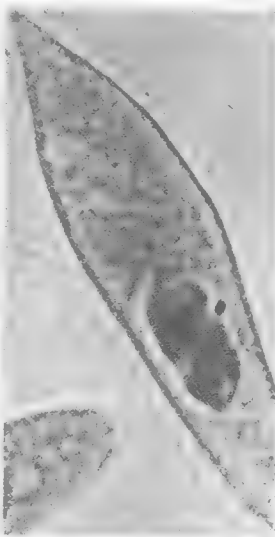
Headquarters of the Cell—the Nucleus

The most prominent feature of eucaryotic cells is the nucleus. The contents of the nucleus are separated from the cytoplasm of the cell by the nuclear membrane. This membrane appears to prevent the free exchange of molecules



Above: Cells have a variety of forms. In this photomicrograph of the undersurface of a leaf, three cell types can be seen. Long conducting cells make up the veins of the leaf. The entrances to the stomata (pores through which carbon dioxide passes into the leaf) are each surrounded by two guard cells. The remaining cells are the epidermal cells ('skin' cells) of the leaf.

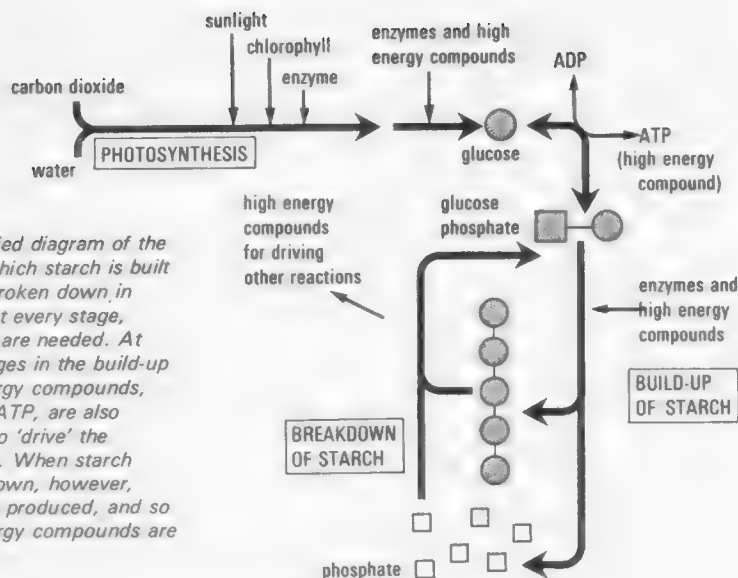
Below: *Paramecium* is one of the many singled-celled organisms that live in fresh water. It moves by waving tiny projections, called cilia, on its outer surface.



and ions from the outer regions of the cell, while allowing the passage of macromolecules (giant molecules) such as *ribonucleic acid* (RNA) —a chemical involved mainly in the manufacture of protein.

The nucleus contains a granular substance called chromatin which is composed of *deoxy-ribonucleic acid* (DNA) and RNA in close association with protein. DNA is a chemical that contains all the 'information' needed for the growth, reproduction and maintenance of the organism. Just before the cell divides, the chromatin becomes visible as threadlike chromosomes made up of DNA, the material which contains the 'genetic code'.

Within the nucleus is a denser structure called the *nucleolus*. This contains large amounts of RNA and protein, and a small piece of chromosomal DNA. This DNA is known as the nucleolar organizer; it directs the formation of the nucleolus itself and of ribosomal RNA. Ribosomal RNA is found on *ribosomes*, structures scattered throughout the cytoplasm. Protein formation occurs on the ribosomal RNA. Nucleoli vary in size from cell to cell, being larger and denser in those cells that carry out active protein synthesis.



A simplified diagram of the way in which starch is built up and broken down in plants. At every stage, enzymes are needed. At most stages in the build-up high-energy compounds, such as ATP, are also needed to 'drive' the reactions. When starch breaks down, however, energy is produced, and so high-energy compounds are made.

Protein Factories—the Ribosomes

The ribosomes are made up of about 60 per cent RNA and 40 per cent protein. In cells that produce protein, they are often found in clusters called *polysomes* or attached to the membranes of the *endoplasmic reticulum*. This structure consists of a folded membrane, which makes up a system of tubules and sacs. Proteins formed on the ribosomes are released into these sacs before being transported to other parts of the cell or to neighbouring ones.

The 'orders' from the nucleus for protein formation are carried to the ribosomes by another type of RNA, called *messenger RNA*, or *m-RNA*. The proteins are formed on the ribosomes by a complex process. Each strand of m-RNA will only make a particular protein. Most of the proteins go to make up new tissue during growth, or to repair damaged structures. They also provide the protein that we and other animals need in our diets.

Enzymes

Another important class of proteins made on the ribosomes are *enzymes*. Enzymes are metabolic catalysts without which most of the cell's chemical reactions could not take place. Enzymes are regarded as catalysts because they are not consumed in the chemical reactions they make possible. They are generally specific for one particular chemical reaction. Occasionally they can catalyse more than one reaction. Some enzyme reactions are further complicated by the need for other chemicals to be present before the reaction can proceed. These other chemicals are called *co-enzymes*, the best known of which are the vitamins. These are chemicals that the body cannot manufacture. They must, therefore, be included in the diet (see page 258).

Exporting from the Cell

Another folded membrane structure within the cytoplasm is known as the *Golgi apparatus*. Similar in appearance to the endoplasmic reticulum, the Golgi apparatus has a major function in packaging and transporting ma-

terials which are to be secreted outside the cell. Substances, such as enzymes, collect in the vesicles of the Golgi apparatus. The vesicles then detach themselves and travel through the cytoplasm to the cellular membrane. Once there, they fuse with the membrane, releasing their contents to the environment outside the cell.

Powerhouses of the Cell—the Mitochondria

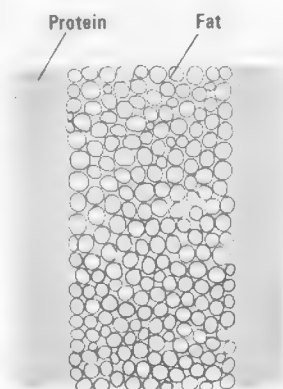
All the processes that occur within a cell require energy. This energy comes from the *mitochondria*, the 'cellular power plants'. Mitochondria are small, oval organelles, and it is here that cellular respiration takes place. Cells that have high energy requirements, such as muscle cells, have many large mitochondria. Cells with low energy requirements have smaller mitochondria in fewer numbers.

Inside the mitochondria, metabolites are broken down by a series of oxidation reactions to carbon dioxide, water and metabolic energy. The energy produced is held in the form of high-energy chemicals. Adenosine triphosphate, or ATP, is a chemical compound of considerable importance in the transfer of energy within the cell. Molecules of ATP take part in a series of enzyme-controlled reactions, during which they lose one of their phosphate groups, and a great deal of energy is released. The energy is then available for processes such as muscle contraction and further chemical syntheses. The loss of a phosphate group from ATP converts it into adenosine diphosphate (ADP). The low-energy ADP molecules are reconverted to the high-energy ATP at the mitochondria, enabling it to be used again.

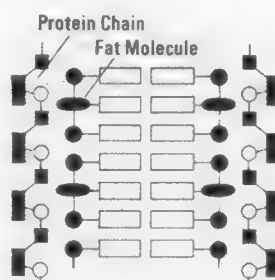
The energy required to convert ADP to ATP usually comes from the breakdown of food substances within the cell. But when the energy required exceeds the immediate food supply, as in severe exertion, more energy can be obtained by the breakdown of food storage compounds. In plant cells, the energy stores are made up principally of starch, although some cells also contain oil droplets for energy storage. Starch is a polymer of glucose, and is similar in structure to the animal equivalent, glycogen. Animals store glycogen in their muscles and liver, but they also store energy in fat under the skin.

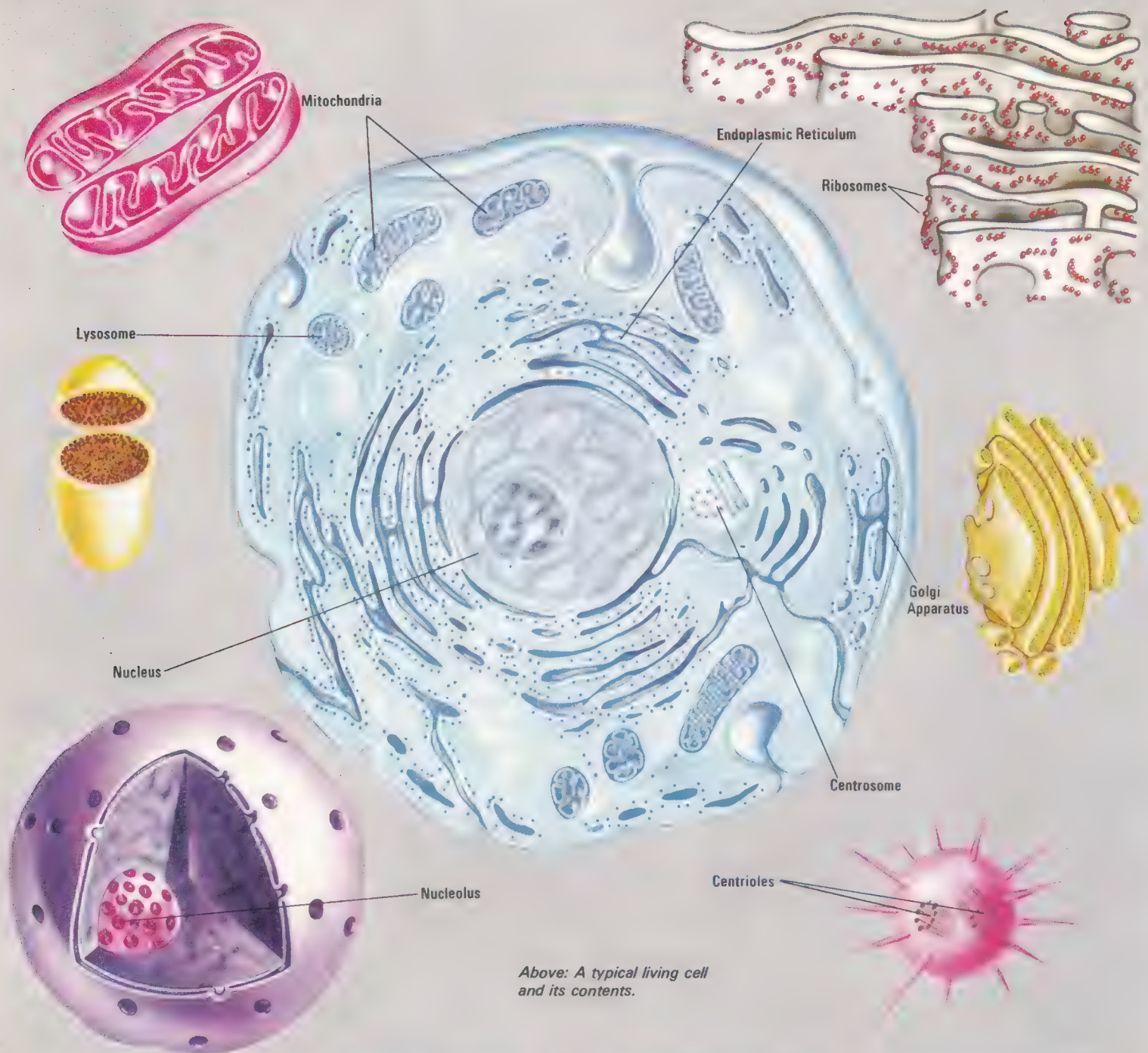
Lysosomes

The cell also contains the means of removing its organic 'rubbish'; for example, fragments of ingested food particles and micro-organisms. Its refuse disposers are the *lysosomes*. These are 'packets' of hydrolytic enzymes which take in particles and break them down. When the lysosome's function is completed, it is expelled from the cell. The lysosomes are also the key to the destruction of dead and dying cells. The membrane surrounding the lysosome breaks down releasing the enzymes into the cytoplasm. These enzymes swiftly break down the cell's macromolecules, leading to its death and disintegration.



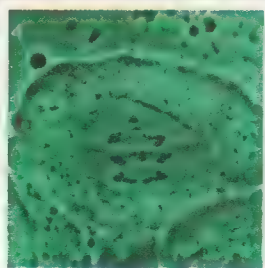
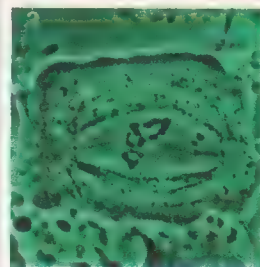
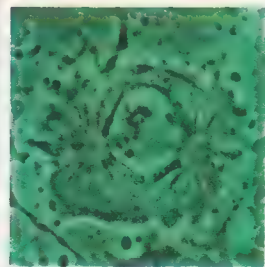
Above: Under the electron microscope, a cell membrane appears to consist of three layers. Biologists have interpreted these layers as being two outer layers of protein with a layer of fat in the middle. Below: A suggested chemical structure of the cell membrane. The outer layers are composed of protein chains (see page 264), and in the middle are molecules of fat (see page 242).





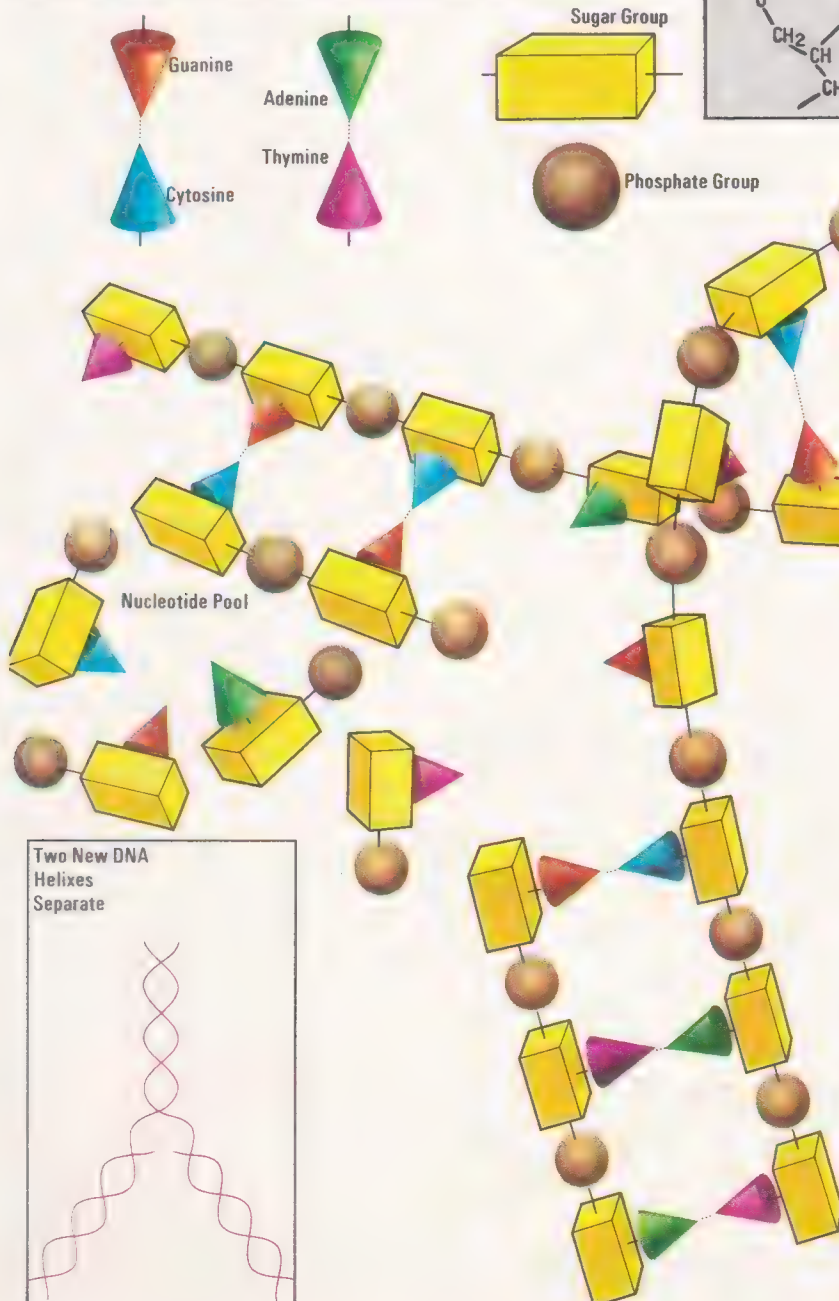
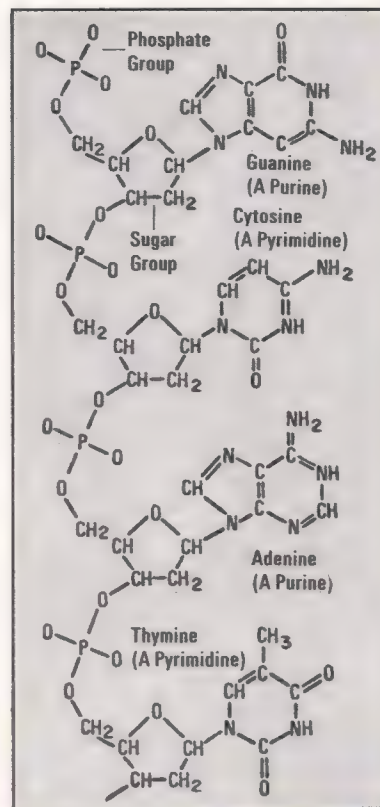
Above: A typical living cell and its contents.

Right: When a cell divides, it passes through several phases. The complete process is called mitosis. During early prophase (1), the chromosomes become visible and divide into two chromatids. In late prophase (2), the nuclear membrane dissolves, and the two centrioles (contained in the centrosome) form a spindle. During metaphase (3), the chromosomes form up on a 'plate' along the centre of the cell. During early anaphase (4), the chromatids separate, and the spindle draws one from each pair to the poles of the cell (5). In telophase (6), the whole cell divides, eventually forming two new cells.



Body Builders

An animal's tissues are built up from its food. But animals cannot make food for themselves. They depend basically on plants for food, because plants can manufacture food. Plants absorb water from the soil and carbon dioxide from the air. During *photosynthesis* they use sunlight to turn these into carbohydrates. Thus plants provide the first step in building up food for animals. But the food absorbed by an animal cannot be used immediately for body building. It must first be broken down into its chemical components and then rebuilt into new compounds. During digestion, food is broken down into soluble chemicals which are easily absorbed by the body's cells. Inside the cells, some of these are built up again into



The chromosomes of a cell contain DNA (deoxyribonucleic acid). A molecule of DNA is made up of two long chains coiled round each other into a form called a double helix. Each chain consists of alternate sugar and phosphate groups and the sugar groups are linked to purine or pyrimidine bases (insert above). The bases of DNA are adenine, thymine, guanine, and cytosine. When the two chains are coiled together, the bases of one chain pair off with the bases of the other chain. Adenine always pairs with thymine, and guanine always pairs with cytosine. When DNA divides, the chains uncoil. New nucleotides (combinations of sugar, phosphate and base) form up on the exposed parts of the chains. The new bases pair up as before, and the sugar and phosphate groups link up to form a chain. Thus two new DNA molecules are made that are both identical to the original molecule. As the new molecules are formed, they coil up and separate (insert left).

body-building substances, while others are used immediately for energy, or stored.

Energy in animal cells generally comes from the breakdown of relatively simple sugars, such as glucose. But proteins, the chemicals that make up most of the meat of animal bodies, can have molecular weights reaching into the millions. Proteins are only one type of long-chain polymer that occur in the body. Giant molecules, or macromolecules, also include the nucleic acids DNA and RNA. Fats are the only body builders which are not polymers, but in the body they are often found in close association with protein polymers, as in cell membranes.

Sugar Polymers

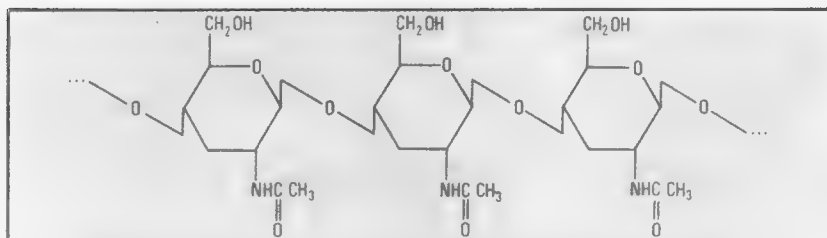
Although sugar in the form of glucose and fructose supplies vital energy, sugar polymers, or *polysaccharides*, play other roles in both animals and plants. Cellulose, which provides the stiff, supporting tissues in plants, is a polymer of glucose, as is the starch that so many plants store. Another polysaccharide is pectin which is found in ripe fruits and some vegetables. It is the presence of pectin in fruit that causes jam to set.

Insects use the polysaccharide chitin to form their hard exoskeletons and it is also included in the shells of crustaceans, such as crabs and lobsters. In higher animals, polysaccharides are present as animal starch, or glycogen, which is stored in the liver and muscles. A related class of compounds, called *mucopolysaccharides*, are found in the skin, cartilage and tendons of animals. The mucopolysaccharides differ from the polysaccharides by the inclusion in their make-up of amine (NH_2) and acid (COOH) groups.

Proteins

Exclude water from the total make-up of the human body, and you will find that three-quarters of what remains is protein. The role of proteins in the body is widespread and varied. They are not only found in the muscle tissue, but also in connective tissue, which is made firm or springy by the proteins *collagen* or *elastin*. Connective tissues link bone to muscle fibres, provide support for organs, and fill spaces in the body cavity.

Blood, too, contains a number of proteins, including antibodies, which are a major

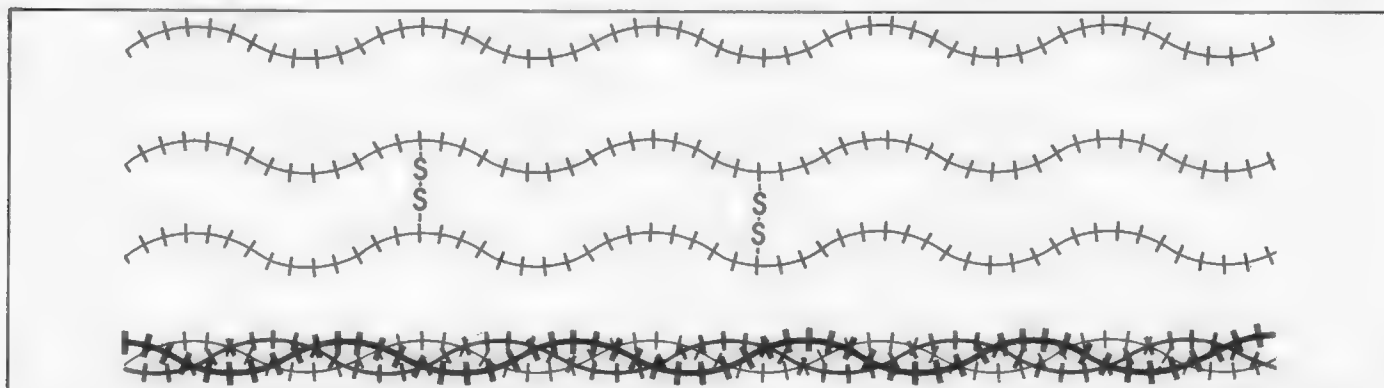
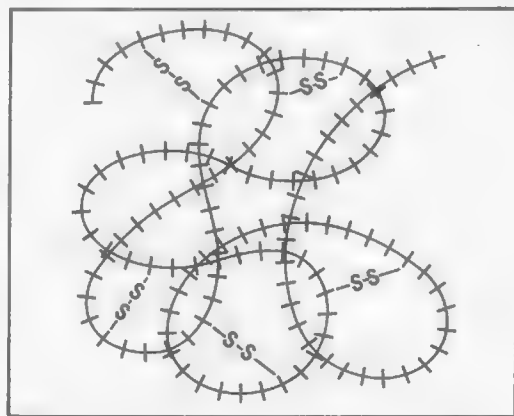


Chitin is a sugar polymer that forms much of the hard outer skeletons of insects, crabs, and other invertebrate animals. This polymer is made up of units of glucose with an attached acetyl-amine group.

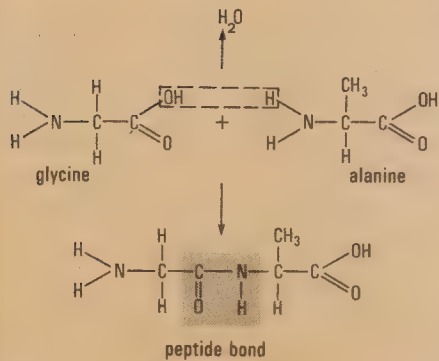
defence against infection. Many proteins are found in the body combined with other substances. For example, fat-proteins, or *lipoproteins*, are found in membranes and *mucoproteins* (proteins containing mucopolysaccharides) are found in connective tissue. Mucus, the sticky fluid which lubricates and protects the breathing and digestive tracts also contains a mucoprotein.

Proteins are composed of chains of amino acids, and each protein has a specific function that is determined by the order of its amino acids. There are 21 different amino acids that may be included in a protein molecule. When such a molecule is formed, amino acids polymerize to form a long chain. The links between the individual units are known as *peptide bonds*. Each amino acid molecule contains an amine (NH_2) group and an acid (COOH) group. The peptide bond is formed by a condensation reaction between the amine group of one molecule and the acid group of the next. The term condensation is used because the link is formed by the loss of one molecule of water. The water molecule is made up of a hydroxyl (OH) group from the acid (COOH) of one amino acid and a hydrogen atom from the amine group of the next acid in the chain. Thus the chain can be built up almost indefinitely. The giant molecules formed, with

Proteins may have one of several shapes. A protein may consist of a single chain of amino acids (in these drawings, each cross-stroke represents one amino acid). Two such chains may be linked together by disulphide bonds (S-S) to form another type of protein. An example is the hormone insulin. The bottom drawing below shows three chains of amino acids coiled together. This structure is found in the fibres of the protein collagen. Globular proteins have convoluted chains of amino acids (right). Examples of such proteins are found in blood. Some globular proteins have two, three, or four of these convoluted chains.



FORMATION OF THE PEPTIDE BOND



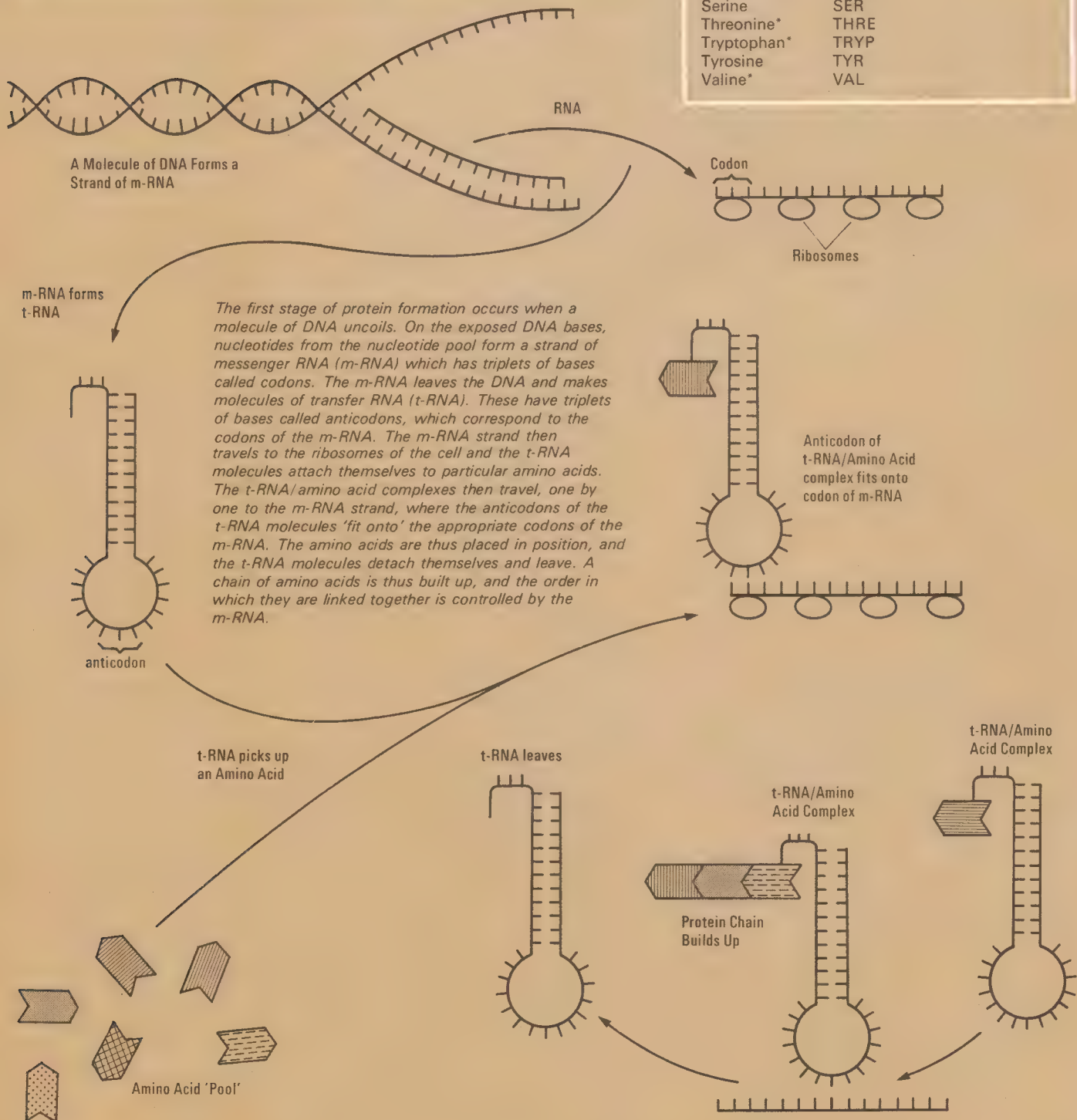
When two amino acid molecules join together to form part of a protein chain, a molecule of water is given off. This leaves the nitrogen atom of one amino acid and a carbon atom of the other with spare bonds. They join up to form a peptide bond.

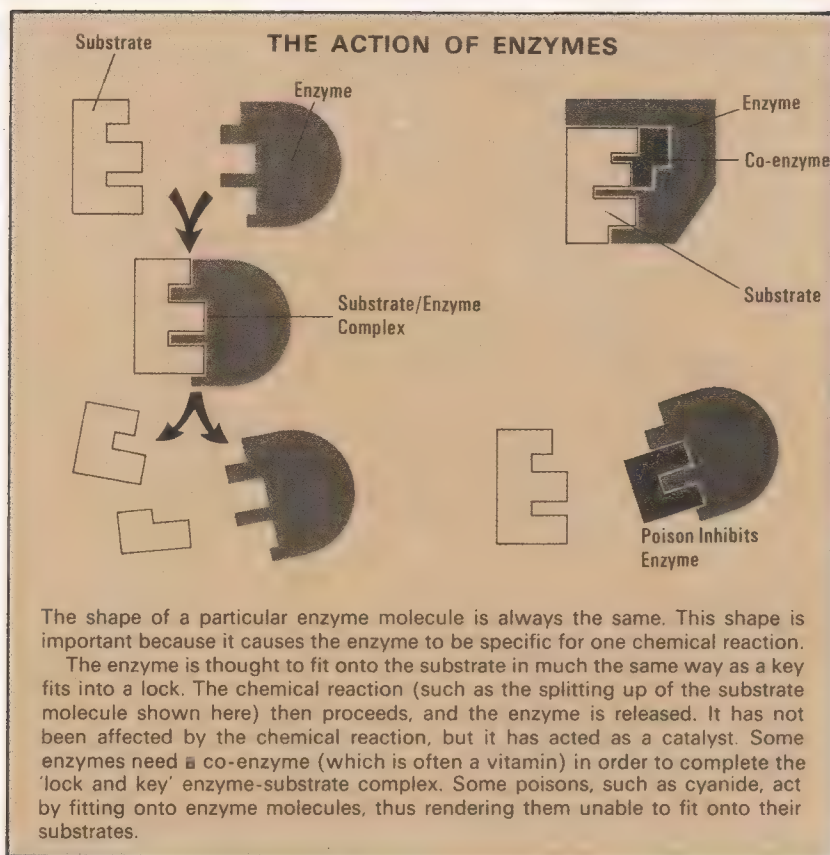
THE AMINO ACIDS THAT MAKE UP PROTEINS

Full Name	Shorthand Name
Alanine	ALA
Arginine	ARG
Aspartic acid	ASP
Cysteine	CYS
Cystine	CYST or (CYS) ₂
Glutamic acid	GLU
Glycine	GLY
Histidine	HIS
Hydroxylysine	HYLY
Hydroxyproline	HYPRO
Isoleucine*	ILEU
Leucine*	LEU
Lysine*	LYS
Methionine*	MET
Phenylalanine*	PHEN
Proline	PRO
Serine	SER
Threonine*	THRE
Tryptophan*	TRYP
Tyrosine	TYR
Valine*	VAL

N.B. Cystine is the dimer (double molecule) of Cysteine.

* Essential amino acids, which must be present in the diet.



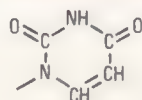


CO—NH bonds between each unit, are called *polypeptides*.

New proteins are built up from proteins taken in as food. These are broken down into their constituent amino acids during digestion and transported to the cell. In the cell the amino acids are regrouped into particular proteins. The order of amino acids in the chain of the new protein molecule is determined by the structure of the RNA which assembles the chain, which is itself determined by the DNA in the nucleus (see diagram). In this way the new protein is tailor-made for its function.

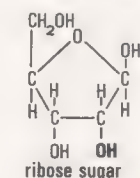
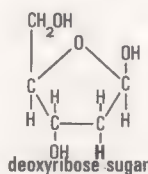
Only the simpler proteins have a straight-chain structure, and even these contain up to 150 amino acids. The more complex proteins usually have inter-twined chains held together by chemical bonds. Apart from the acid (COOH) group and the amine (NH₂) group already mentioned, each amino acid contains a hydrogen atom, a radical (R) group, of which the simplest example is hydrogen, and a central carbon atom to which the other three groups are linked. The bonds between the folds of the protein chains are between the radical groups of the amino acid molecules. Enzymes are more complex proteins, sometimes containing as many as four folded protein chains.

The shapes of polypeptide chains in the body vary considerably. For example, the protein part of the blood pigment haemoglobin is made up of four convoluted chains. Two of these each contain 141 amino acids, and the other two each contain 146 amino acids. But the fibrous proteins that make up the springy connective tissues of the body are more usually



Above: Uracil is a pyrimidine base that forms part of the RNA molecule. The other three RNA bases are adenine, guanine and cytosine (see page 263).

Below: The molecules of ribose and deoxyribose sugars differ in one respect only. Deoxyribose sugar has a hydrogen atom (—H) attached to one of its carbon atoms, instead of the hydroxyl group (—OH) on the equivalent carbon atom of a ribose sugar molecule.



found to have two or more chains coiled round each other to form a spiral or helix.

RNA and DNA

The nucleic acids RNA and DNA are the carriers of all the genetic information in living cells. DNA makes up most of the nuclear material and controls all the functions of the cell. In most cells, RNA is only a working copy of the DNA molecule. It is the 'information' molecule within the cell, carrying messages from the DNA in the nucleus and directing the formation of new protein. It is a polymer, but it is not a protein. The units that make up the chains of RNA and DNA molecules are known as *nucleotide monomers*. Each nucleotide is made up of a sugar, an acid phosphate group and a nitrogen-containing base. In RNA, the sugar is ribose sugar, so the nucleotide monomers are called *ribonucleotides*.

In RNA there are four different types of nucleotide. Each of these has a different nitrogen-containing base. The four bases are two pyrimidines, uracil (U) and cytosine (C), and two purines, guanine (G) and adenine (A). The polynucleotide RNA is formed by linkages between the sugar group of one nucleotide and the phosphate group of the next. This forms a chain of sugar and phosphate groups, and the bases extend off to the side of this chain.

The Double Helix

In DNA (deoxyribonucleic acid), the sugar is deoxyribose sugar. Like RNA, DNA contains a chain of sugar and phosphate groups. DNA also contains three of the same bases, adenine, guanine and cytosine. But DNA includes the base thymine (T) instead of the uracil found in RNA. And where RNA is generally only a single polymer chain, DNA forms a double chain in a helix spiral. The two chains are held together by weak hydrogen bonds between the bases. The bases can only bond with 'partner' bases, A's of one chain always being linked with the T's of the other and the G's always linked to the C's. This means that the sequence of bases on one chain determines the sequence on the other. Thus a sequence of AACGATACC will be matched by TTGCTATGG. Even in a short length of DNA the pairs of bases can be arranged in many different orders. The DNA of a chromosome in any animal or plant cell contains many thousands of pairs of bases arranged in a unique sequence. And it is this variation in the structure of the DNA which produces the variations between living things.

The double helix structure of the DNA molecule is also the key to cell reproduction. To produce identical daughter cells, the DNA must produce a replica of itself. To do this the chains split apart and new nucleotides (there are always free ones in the cell) float in to bond with the newly unlinked bases. Because each base can only link with the appropriate base on the other chain, the two new double chains are identical to the original.

Energy and Growth

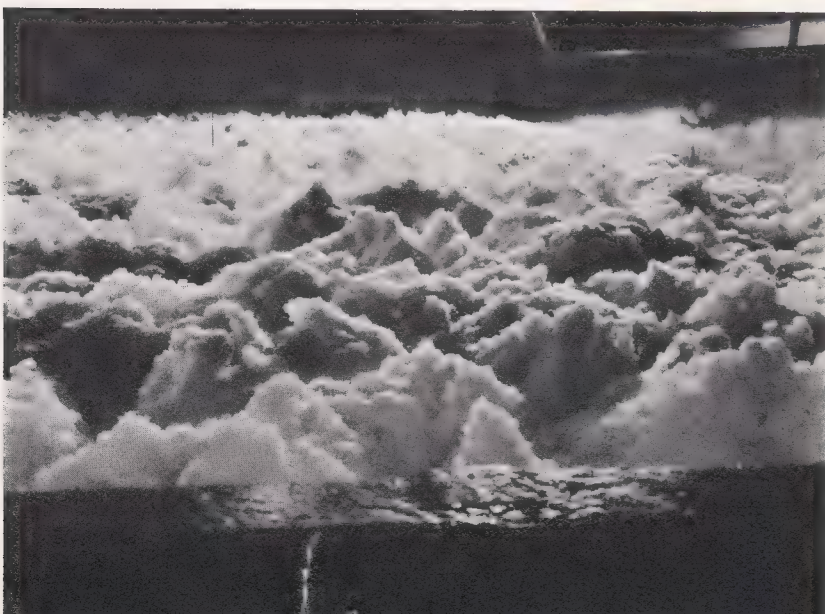
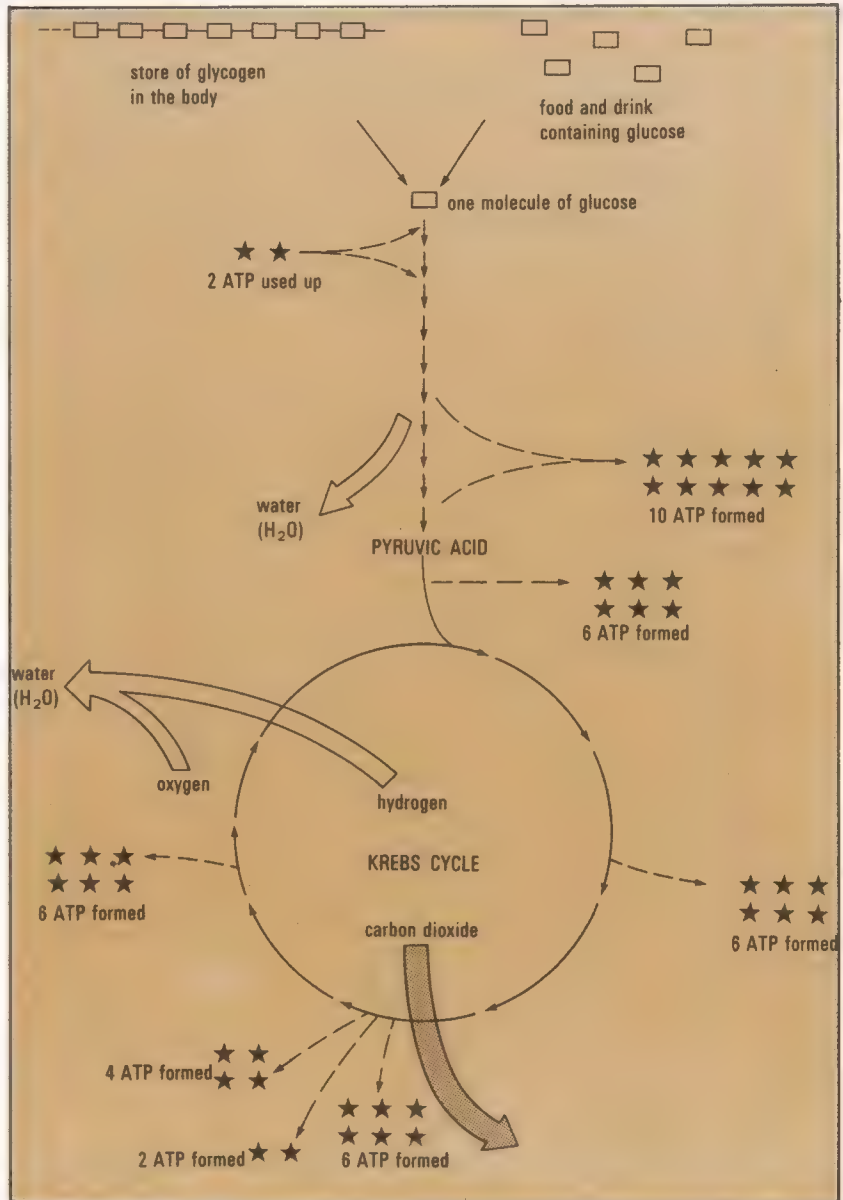
Below: How the bodies of all animals and plants get energy during the process of respiration. Glucose may come directly from food substances, or from glycogen, the polymer form in which glucose is stored in the body. Glucose is broken down in a number of reactions, during which energy is released in the form of ATP. During the whole process, 38 molecules of ATP are formed. The energy that these contain can be used to drive other metabolic reactions.

Energy for all forms of life comes from the Sun. Plants harness solar energy during photosynthesis and pass it on to animals mainly stored in carbohydrates, either directly or via the plant-eating animals that they eat. Animals and plants 'burn' this food to produce energy, just as a car engine burns petrol to produce energy to drive the car. The process by which animals (and plants) release energy from food is respiration. The products of the conversion are *adenosine triphosphate* (ATP) and other high-energy compounds, together with waste in the form of carbon dioxide and water.

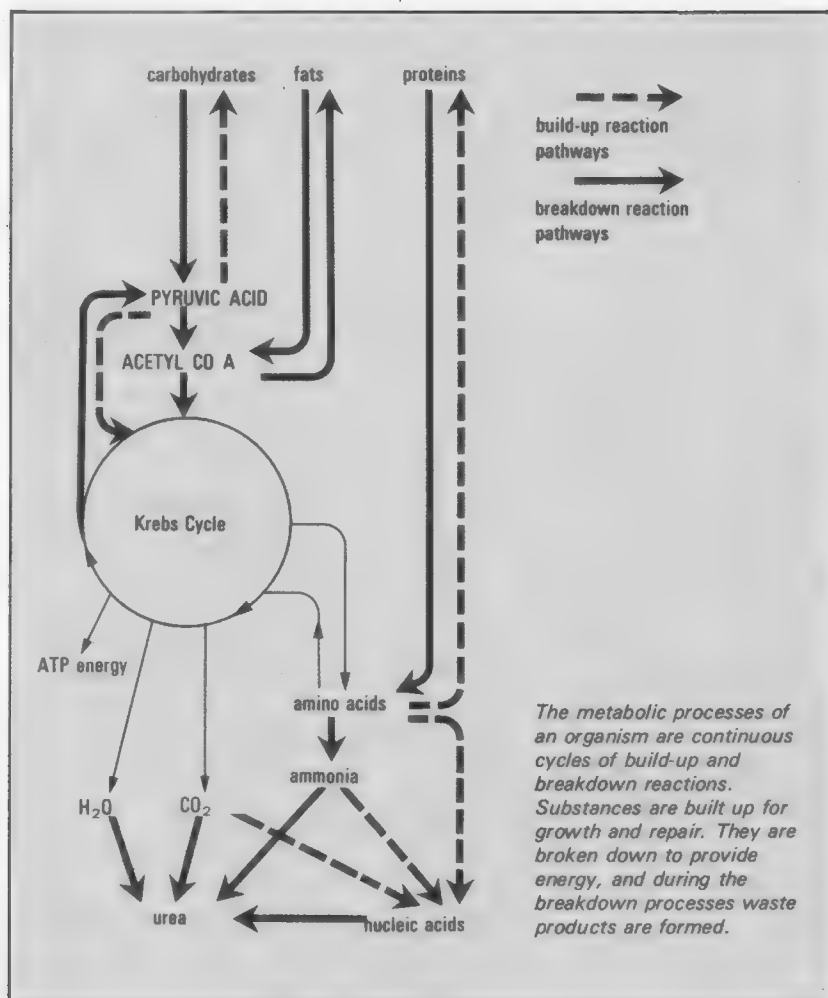
The release of energy from food requires a number of extremely complicated processes. Many complex compounds and enzyme reactions are involved, and reactions in the body that release energy are often linked to other reactions that need energy. So some of the energy that is released is used up immediately in maintaining the chemical processes. Some reactions that occur follow a sequence or chain. Other reactions form part of *cycles*. Biochemists describe these chains and cycles of reactions as *metabolic pathways*.

Releasing Energy

A drink of glucose (an 'energy drink' as the label may describe it) is broken down in the body by about 20 reactions to provide ATP-energy, carbon dioxide, and water (see diagram). Most of the 20 reactions require different enzymes and co-enzymes to make them work. The whole process consists of a chain of reactions leading to a cycle of reactions. Some of which provide ATP-energy. The chain of reactions is the *glucose-breakdown pathway*. The cycle is called the *Krebs cycle*,



Left: The froth on the top of a vat of fermenting beer is caused by yeast. The fermentation of the sugar (in the malt) by yeast occurs in anaerobic conditions. Even so, this is a form of respiration. The chemical process is the same as in the diagram above until pyruvic acid is formed. The Krebs cycle, however, requires oxygen. If no oxygen is available then the pyruvic acid is converted by yeast into ethyl alcohol (ethanol). But this process cannot continue indefinitely. In aerobic respiration, most of the ATP is formed during Krebs cycle. Therefore, when yeast respire anaerobically for some time it will not produce sufficient energy to drive its metabolic reactions. At the same time the accumulation of the alcohol will eventually poison and kill the yeast.



after its discoverer Hans Krebs. The Krebs cycle is an important cycle in biochemistry. During the cycle, not only compounds derived from glucose, but also compounds derived from other foods can be broken down to provide energy. Sugars such as glucose are merely the easiest to break down.

When the sugar reaches the cell, each of its molecules is split into two molecules of pyruvic acid, in a process involving about ten different enzyme reactions. This process liberates only a small amount of ATP-energy. The glucose-breakdown pathway is also known as glycolysis. The Krebs' cycle takes place in the mitochondria, the cell's power plants. Here oxygen breathed in from the air is used to oxidize the pyruvic acid in a series of chemical reactions. These result in the release of carbon dioxide, water and many ATP molecules.

From each molecule of glucose 38 molecules of ATP are formed. The ATP is then available for powering protein synthesis, muscle contraction, hormone release and every other metabolic process. Energy is released by the loss of one phosphate group from the ATP, transforming it to adenosine diphosphate (ADP), which is reconverted to ATP during the Krebs' cycle.

Energy Reserves

Not all the food that passes through the digestive system is used immediately for

energy. Some is diverted from the Krebs' cycle and stored in the form of the starch-like polymer *glycogen* in the liver and muscles. Even more is stored as fat beneath the skin. Excess carbohydrate is converted to fat when pyruvic acid and *acetyl Co A* link up the carbohydrate and fat pathways. If no food comes to the mitochondria directly from the digestive system, then this stored food is broken down. In emergencies, when the sugar and fat reserves have been used up, the Krebs' cycle will even break down the protein tissue of the body. But the process cannot last for long. The body, virtually feeding on itself, soon starves.

The Krebs' cycle is mainly concerned with breaking down materials. But many metabolic processes are linked together by chemical reactions so that the breakdown of one metabolic compound leads to the build-up of another. This, indeed, happens in the Krebs' cycle itself. While breaking down compounds to carbon dioxide and water, it gives rise not only to ATP but also to amino acids. So the Krebs' cycle plays a part in the build-up of proteins, needed for growth and replacing worn-out tissues.

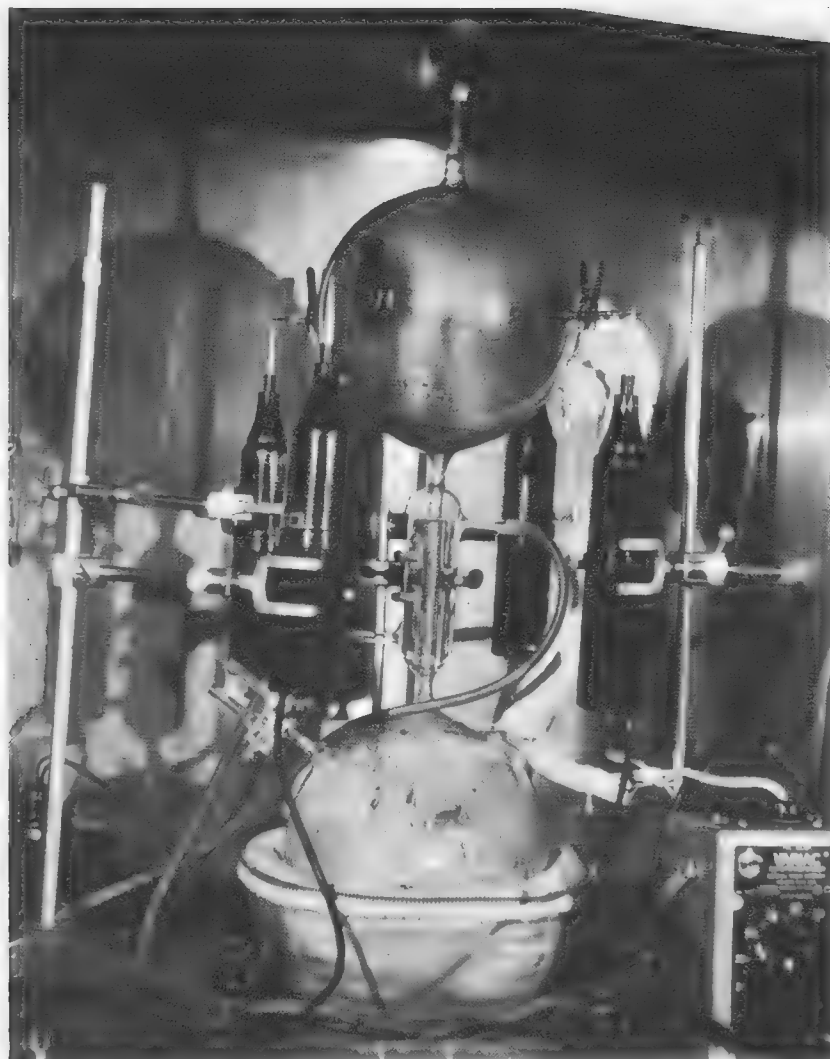
Waste Disposal

The body makes wastes as well as useful products. The process of getting rid of these wastes is called *excretion*. The carbon dioxide that is breathed out, sweat, and urine are all excreted wastes.

When proteins and nucleic acids are broken down, their waste products contain a lot of nitrogen, and the body gets rid of this as *urea*, a compound which contains a high proportion of nitrogen as its formula, $\text{CO}(\text{NH}_2)_2$, shows. Urine is mainly urea plus water. Urea is a fairly harmless waste which can be stored for a while before being passed out of the body, and so it is a suitable waste product for a land animal. Fishes, on the other hand, do not need to store their nitrogen waste. They get rid of it as ammonia, which is poisonous, but is immediately diluted and made harmless by the water in which the fishes live.



Overeating may result in becoming fat. This is the result of taking in more carbohydrates than the body needs to provide itself with energy. The excess carbohydrates are converted to fat and stored, frequently beneath the skin.



Life, Viruses and Genes

The First Signs of Life

For millions and millions of years the Earth was lifeless. Its atmosphere was a lethal mixture of ammonia, methane, hydrogen and carbon dioxide. As the young planet cooled water vapour in the atmosphere condensed and a deluge of rain lashed the land for thousands of years, to produce the oceans. And from these oceans came life. Chemical compounds, including those of carbon, were formed in the atmosphere and washed into the sea, where they formed a rich chemical 'soup'. Ceaseless chemical activity made possible the formation of a compound that could reproduce itself; self-reproduction being an essential characteristic of living organisms. This first self-reproducing compound was probably similar to the giant molecule of DNA.

In the watery fluid of the living cell, DNA can reproduce itself when supplied with

Above: Part of the experimental apparatus used to test the idea that the first amino acids could have been formed from the ammonia, methane, and hydrogen in the Earth's primitive atmosphere. Electric sparks were passed through a mixture of these gases in steam. After this had been done for some time, organic compounds were found in the water.

suitable compounds. Biochemists can even now make this happen in the laboratory outside a cell. It is probable, therefore, that, more than 1000 million years ago, giant molecules resembling nucleic acids first reproduced themselves, with the aid of a concentrated solution of supply compounds from the *primeval soup*.

Life from Lightning

Proof that life could have originated in this way has come from experiments carried out some years ago in the United States. A mixture of gases, of the kinds that existed in the atmosphere of Earth 1000 million years ago, were sparked with electrical flashes in a glass chamber which also contained water. The electric sparks resembled miniature flashes of lightning in the primeval atmosphere.

When, after a number of 'lightning flashes', the water was analysed, it was found to contain such compounds as purines and amino acids, which had been formed by chemical reactions between the gases, aided by the electrical energy. The compounds formed were, in fact, those that build up to the giant molecules in cells: they are the supply compounds of nucleic acids and proteins.

Over millions of years such compounds would have formed, and broken down, over and over again, until at last, in some particularly favourable conditions, giant molecules were formed which could reproduce themselves. But they would still have been defenceless against other chemicals that were poisonous to them. A cell is protected from its environment by the cytoplasm that surrounds its nucleus and the cell membrane that prevents the invasion of unwanted chemicals. Research has shown that the fatty materials and proteins needed to form these membranes were present in the ancient seas. And by wrapping themselves in such protective materials, the giant molecules could have transformed themselves into primitive cells.

Viruses

Like the ingredients of the primeval soup, viruses do not consist of cells, yet they do reproduce themselves. They were discovered less than a century ago and only in the last thirty years have many viruses been described fully. This is because they are so very small that they can be seen only with the electron microscope.

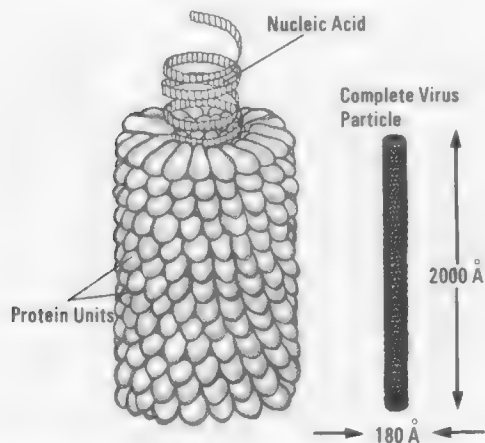
The simplest viruses, such as those that give us colds, are less than one ten thousandth of a millimetre in size and consist only of protein and ■ nucleic acid. In some of them, molecules of protein 'wrap up' a molecule of the nucleic acid RNA to make a round parcel. Some other simple viruses are similar, but rod-shaped, packages. Yet others contain DNA, not RNA, and larger, more complex viruses contain fatty substances as well.

The largest viruses are about the same size as the smallest cells, but their structure is quite different from the complex structure of

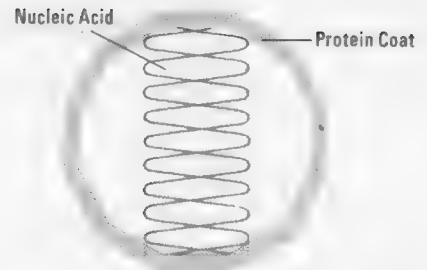
the cell. Also, no organism resembling both viruses and cells has ever been found. For these reasons, biologists think that viruses are not the ancestors of cells, but have arisen, either separately from the 'organisms' that existed in the primeval soup, or from cells themselves. The fact that viruses cannot reproduce without living cells certainly supports this latter theory.

Viruses can, in fact, only function inside a cell. The nucleic acid invades the cell and gives orders for the reproduction of the virus, but this can only be accomplished with the help of the cell's own nucleic acids. Experiments show that a cell, when infected with the nucleic acid of a virus (which is all that enters the cell) will make not only virus nucleic acid but also virus protein. These usually come together and assemble inside the cell to make the complete virus particles. The word 'assemble' indicates that the virus can be considered as an object that can be put together rather than a living thing that grows.

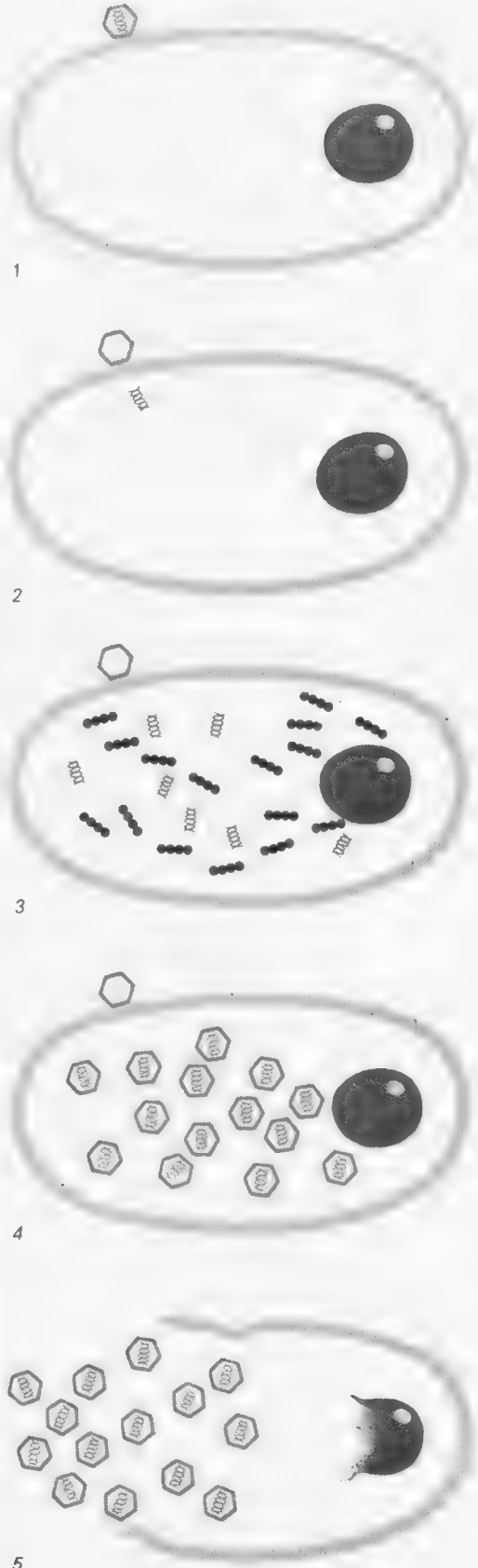
A small virus, compared with a cell, has a very simple construction. A larger virus, with its outer coat of fat-protein, surrounding an inner mixture of nucleic acid and protein, resembles in these ways the nucleus of a cell.



Right: A cross-section of a simple polyhedral virus. It consists only of a nucleic acid molecule (RNA or DNA) surrounded by a coat of protein.

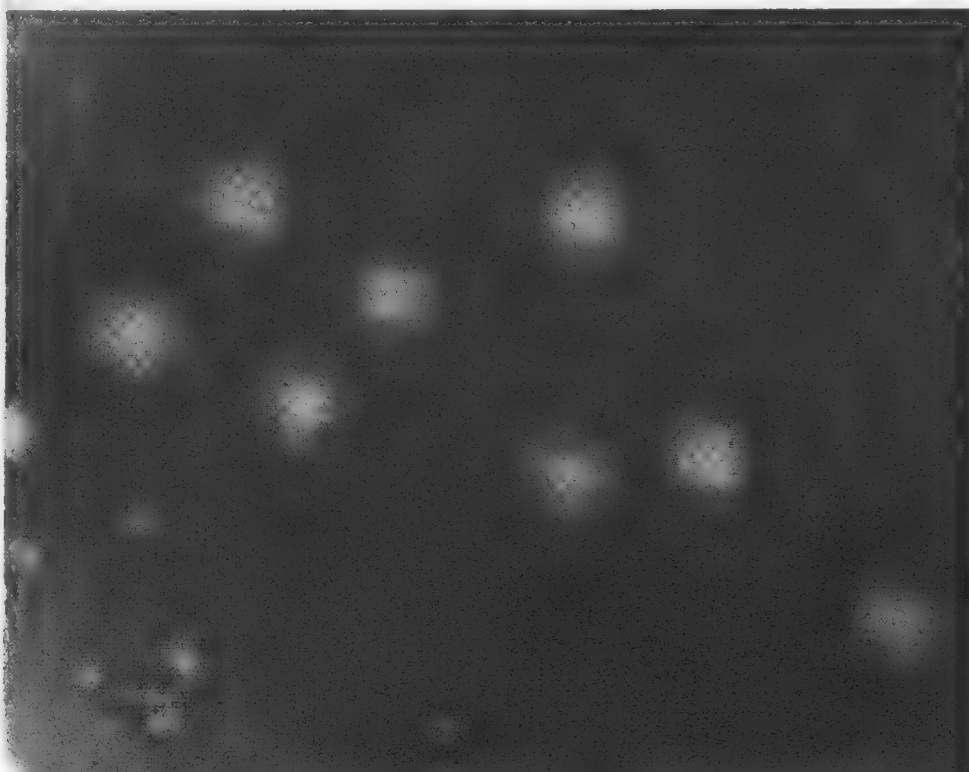


Right: How a virus reproduces. 1. The virus sticks to the cell. 2. It injects its nucleic acid into the cell. The protein coat remains behind. 3. The virus nucleic acid orders the cell to make virus components — nucleic acid and protein. 4. The virus components in the cell join up to make complete virus particles. 5. The cell may then break down, releasing the new virus particles.



Left: Some viruses have a rod-like shape. Such viruses are built up from many protein units which surround a central spiral of nucleic acid, as shown in the cutaway drawing. The diameter of a complete rod-like virus is only about 180 Angstrom units (18 millionths of a millimetre), and its length is about 2000 Angstrom units.

Below: An electron micrograph of some polyhedral viruses. These are magnified 24,000 times.



Therefore, whatever the difference between a cell nucleus and a virus, they have one thing in common—they both possess the 'blueprint' for reproduction.

Genes and Reproduction

Inside the nucleus of a living cell, DNA gives the orders for all the activities of the cell. On these orders, enzymes are made for regulating the chemical reactions of the cell, and other proteins are made for growth.

But both in animals and plants, growth is caused by an increase in the *number* of cells. Cells in the body reproduce by dividing into two. The DNA in the cell nucleus has all the information necessary to cause the cell to reproduce, and gives the orders for it to do so. But the DNA of a many-celled animal or plant contains much more information, enough for the reproduction of the whole organism.

The DNA in the cells of the human body contains all the information that makes up an individual. For example, if a man has red hair, then his DNA contains the information necessary for producing red hair. If he has blue eyes, his DNA has information for blue eyes.

Scientists refer to the factors that control such characteristics as *genes*. If a man has red hair and blue eyes, and his son has the same characteristics, then the son is said to have inherited his father's genes. If this is so, then the genes responsible must be in the DNA of the cells of both father and son. In fact, genes are *parts* of the DNA. As a whole, DNA contains all the information and gives all the orders. Genes contain part of the information and give single orders.

How Many Genes?

Molecules of DNA and other nucleic acids consist of repeated units linked together. Each unit consists of a nitrogen base attached to a sugar which is itself attached to a phosphate group. A gene, being part of a nucleic acid molecule, consists of a certain number of these linked units. The average gene, in fact, contains about 1000 such units. In human beings, character such as colour of eyes would be controlled by one or two of these genes. More general characters such as tallness or shortness are controlled by many genes.

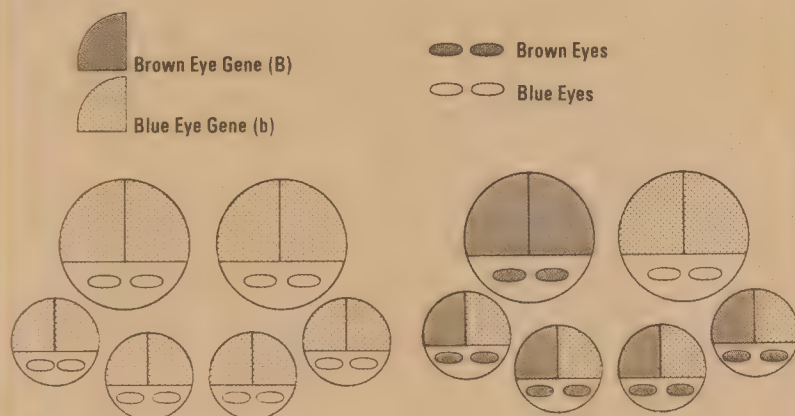
Viruses contain only a single molecule of nucleic acid, and this gives all the orders necessary for the reproduction of the virus. The nucleic acid of a simple virus contains only about 10 genes, which give such orders as 'make virus protein' and 'make virus nucleic acid' and, furthermore, 'put them together to make a virus'.

The number of orders necessary to make a plant or animal is very large indeed and so the DNA of these organisms contains a great number of genes. In their cells the DNA is contained in chromosomes, together with some protein. The cells of human beings each contain 46 chromosomes, which contain many thousands of genes.

INHERITANCE OF EYE COLOUR

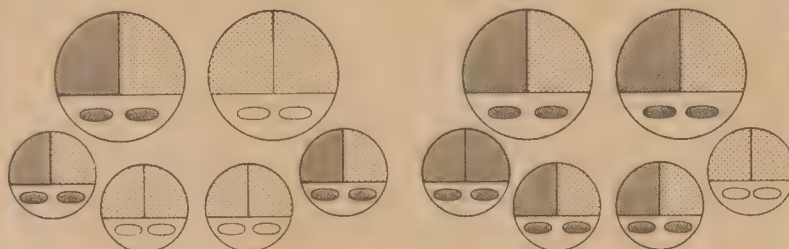
The colour of children's eyes depend on the eye colours of their parents. Such characteristics are controlled by *genes*, which are carried on the *chromosomes*. Human beings have 46 chromosomes, made up of 23 pairs, in all their cells except their sex cells. When the sex cells are formed a 'reduction division', called *meiosis*, occurs. One chromosome from each pair goes into a sex cell, so that it contains only 23 single chromosomes.

A parent's eye colour is controlled by two genes, which are carried on one pair of chromosomes. A parent who has two brown eye genes (BB) will have brown eyes, and a parent who has two blue eye genes (bb) will have blue eyes. But a parent who has one brown eye gene (B) and one blue eye gene (b) will have brown eyes. This is because brown is *dominant* to blue, which is called *recessive*.



If both parents have two blue eye genes (bb) each, all their children will have blue eyes. No dominant brown eye genes are present, and so the recessive blue-eye genes are allowed to show in both parents and children.

If one parent has two brown eye genes (BB), and the other parent has two blue eye genes (bb), their children will each inherit one brown eye gene and one blue eye gene. But they will all have brown eyes because the brown eye gene is dominant.



A parent who has one brown eye gene (B) and one recessive blue eye gene (b) will have brown eyes. But if the other parent has blue eyes (bb), their children have an equal chance of having brown or blue eyes.

If both parents each have one brown eye gene (B) and one blue eye gene (b), their children are most likely to have brown eyes. But blue-eyed children are still possible.

Because of the 'reduction division' process, sex cells only contain one eye-colour gene. The sex cells of a pure brown-eyed parent (BB) contain only brown eye genes (B), and the sex cells of a blue-eyed parent (bb) contain only blue eye genes. But the sex cells of a brown-eyed parent who has both genes (Bb) will not all be the same. Half of them will contain brown eye genes (B) and half will contain blue eye genes (b).

Children therefore receive two eye-colour genes, one from each parent. When the sex cells combine, the eye-colour combinations may be BB, bb, Bb or bB. Three of these combinations lead to brown eyes. Only bb guarantees blue eyes. Blue-eyed parents will thus have blue-eyed children. They have no brown eye genes to pass on. Brown-eyed parents (unless they are both BB) can, however, produce blue-eyed children. If both have a B and b gene, their children may inherit the two b genes. In other words, a brown-eyed person can be a 'carrier' of the recessive blue eye gene. He has it but does not show it.

MELTING AND BOILING POINTS OF THE ELEMENTS

Element	MP(°C)	BP(°C)	Element	MP(°C)	BP(°C)	Element	MP(°C)	BP(°C)
Actinium	1230	3200	Hafnium	2230	5300	Promethium	1000	2700
Aluminium	660.4	2350	Helium	3.5 K	4.22 K	Protactinium	1200	4000
Americium	990	2600	Holmium	1470	2300	Radium	700	1500
Antimony	630.7	1640	Hydrogen	-259.2	-252.8	Radon	-71	-62
Argon	-189.4	-185.9	Indium	156.6	2050	Rhenium	3180	5600
Arsenic	613 solid sublimates		Iodine	113.6	184	Rhodium	1963	3700
Astatine	300	350	Iridium	2447	4550	Rubidium	38.8	705
Barium	710	1640	Iron	1540	2760	Ruthenium	2310	4100
Berkelium	986		Krypton	-157.3	-153.4	Samarium	1060	1600
Beryllium	1285	2470	Lanthanum	920	3450	Scandium	1540	2800
Bismuth	271.4	1650	Lead	327.5	1760	Selenium	220	685
Boron	2030	3700	Lithium	180	1360	Silicon	1410	2620
Bromine	-7.1	58.9	Lutetium	1700	3400	Silver	961.9	2160
Cadmium	321.1	770	Magnesium	650	1100	Sodium	97.8	900
Caesium	28.6	686	Manganese	1250	2120	Strontium	770	1380
Calcium	840	1490	Mercury	-38.9	356.6	Sulphur	115	444.7
Carbon	3700 solid sublimates		Molybdenum	2620	4830	Tantalum	3000	5400
Cerium	800	3000	Neodymium	1024	3100	Technetium	2200	4600
Chlorine	-101	-34.0	Neon	-248.6	-246.0	Tellurium	450	990
Chromium	1860	2600	Neptunium	648		Terbium	1360	2500
Cobalt	1494	2900	Nickel	1455	2150	Thallium	304	1460
Copper	1084.5	2580	Niobium	2425	5000	Thorium	1700	4500
Curium	1340		Nitrogen	-210	-195.8	Thulium	1550	2000
Dysprosium	1410	2600	Osmium	3030	5000	Tin	231.9	2720
Erbium	1520	2600	Oxygen	-218.8	-182.9	Titanium	1670	3300
Europium	820	1450	Palladium	1554	3000	Tungsten	3387	5420
Fluorine	-219.6	-188.1	Phosphorus	44.2 (yellow)	280.4	Uranium	1135	4000
Francium	30	650	Platinum	1772	3720	Vanadium	1920	3400
Gadolinium	1310	3000	Plutonium	640	3200	Xenon	-111.9	-108.1
Gallium	29.8	2070	Polonium	254	960	Ytterbium	824	1500
Germanium	959	2850	Potassium	63.2	777	Yttrium	1510	3300
Gold	1064.4	2850	Praseodymium	935	3000	Zinc	419.6	913
						Zirconium	1850	4400

NAMES OF CARBON COMPOUNDS

Carbon compounds were originally given names as they were discovered, and these are now their common names. More recently many of these names were changed by international agreement. These IUPAC names are intended to describe the compound more accurately. In this book, organic chemicals are mostly given their common names. The IUPAC names of organic chemicals described in this book are given below.

Common Name	IUPAC Name
Acetaldehyde	Ethanal
Acetic acid	Ethanoic acid
Acetophenone	Phenyl ethanone
Acetone	Propanone
Acetonitrile	Ethanonitrile
Acetylene	Ethyne
Aniline	Phenylamine
Benzaldehyde	Benzenecarbaldehyde
Benzonitrile	Benzenecarbonitrile
Butyl alcohol	Butanol
Butylene	Butene
Carbon tetrachloride	Tetrachloromethane
Carbon tetrafluoride	Tetrafluoromethane
Chloral	Trichloroethanal
Chloroform	Trichloromethane
Diethyl ether	Ethoxyethane
Ethane	Ethane
Ethyl acetate	Ethyl ethanoate
Ethyl alcohol	Ethanol

Common Name	IUPAC Name
Ethyl chloride	Chloroethane
Ethylene	Ethene
Ethylene tetrafluoride	Tetrafluoroethane
Formaldehyde	Methanal
Formic acid	Methanoic acid
Fumaric acid	Transbutenedioic acid
Iodoform	Triiodomethane
Maleic acid	Cisbutenedioic acid
Malonic acid	Propanedioic acid
Methyl alcohol	Methanol
Methyl chloride	Chloromethane
Methyl cyanide	Ethanonitrile
Methylene chloride	Dichloromethane
Methylene iodide	Diiodomethane
Oxalic acid	Ethanedioic acid
Phenol	Benzenol
Phenyl cyanide	Benzenecarbonitrile
Phenyl isocyanide	Benzene isocarbonitrile
Phosgene	Carbonyl chloride
Polyethylene	Polyethene
Polypropylene	Polypropene
Propionic acid	Propanoic acid
Succinic acid	Butanedioic acid
Toluene	Methylbenzene
Trichlorethylene	Trichloroethene
Urea	Carbamide
Vinyl chloride	Chloroethene
Vinylidene chloride	Dichloroethane

ALLOYS

Name	Composition
Aluminium bronze	90% Cu, 10% Al
Manganese bronze	95% Cu, 5% Mn
Gun Metal Bronze	90% Cu, 10% Sn
Red brass	90% Cu, 10% Zn
Naval brass	70% Cu, 29% Zn, 1% Sn
Yellow brass	67% Cu, 33% Zn
Nickel silver	55% Cu, 18% Ni, 27% Zn
Steel	99% Fe, 1% C
Stainless steel	Fe with 0.1-2.0% C, up to 27% Cr or 20% W or 15% Ni and lesser amounts of other elements
18-carat gold	75% Au, 25% Ag & Cu
Palladium, or white gold	90% Au, 10% Pd
Sterling silver	92.5% Ag, 7.5% Cu
US silver	90% Ag, 10% Cu
Britannia metal	90% Sn, 10% Sb
Dentist's amalgam	70% Hg, 30% Cu
Type metal	82% Pb, 15% Sb, 3% Sn
Pewter	91% Pb, 7% Sb, 2% Cu

PHYSICAL CONSTANTS

<i>c</i>	speed of light	$2.997925 \times 10^8 \text{ m/s}$	<i>e</i>	charge of electron	$1.60210 \times 10^{-19} \text{ C}$
<i>G</i>	gravitational constant	$6.670 \times 10^{-11} \text{ N m}^2/\text{kg}^2$	<i>m_e</i>	rest mass of electron	$9.1091 \times 10^{-31} \text{ kg}$
<i>g</i>	acceleration due to gravity	9.80665 m/s^2	<i>r_e</i>	radius of electron	$2.81777 \times 10^{-15} \text{ m}$
π	circum./diam. circle	3.14159265	<i>m_p</i>	rest mass of proton	$1.67252 \times 10^{-27} \text{ kg}$
<i>e</i>	base of natural logarithms	2.71828	<i>m_n</i>	rest mass of neutron	$1.67482 \times 10^{-27} \text{ kg}$
<i>R</i>	gas constant	8.3143 J/K mol.		speed of sound at sea level at 0°C	331.7 m/s (742 mph)
<i>N_A</i>	Avogadro's constant	$6.02252 \times 10^{23} \text{ per mole}$		standard temperature and pressure	0°C and $1.01325 \times 10^5 \text{ Pa}$
<i>h</i>	Planck's constant	$6.6256 \times 10^{-34} \text{ J s}$		standard atmosphere	$1.01325 \times 10^5 \text{ Pa}$
<i>F</i>	Faraday's constant	$9.64870 \times 10^4 \text{ C/mol}$		melting point of ice	0°C or 273.15 K

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